Science and Technology Policy Institute

E-Vision 2000:
Key Issues That Will Shape Our Energy Future

Analyses and Papers Prepared for the E-Vision 2000 Conference

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Preface

This report documents a May 2000 initiative by the Office of Energy Efficiency and Renewable Energy (EERE) of the U.S. Department of Energy (DOE) to identify and assess a range of emerging issues that may affect future energy use and supply. EERE contracted with RAND's Science and Technology Policy Institute to plan and execute a strategic planning project. The project's purpose was to explore possible new approaches to energy supply and use, identify key issues EERE will face, and consider the implications for EERE's research and development (R&D) portfolio. EERE was interested in developing a systematic process to better understand the implications of emerging issues for future R&D, federal assistance programs, public information dissemination, education, and technical training.

The project had three parts: (1) a conference called E-Vision 2000, held October 11–13, 2000 in Washington, D.C., including presentation of invited papers; (2) an assessment of long-range planning scenarios currently used in the energy community; and (3) a structured process to identify a set of critical energy issues in 2020 to inform the EERE R&D portfolio, as viewed by a range of experts.

This report summarizes the issues raised and suggestions made for future research by the participants in and attendees of the E-Vision 2000 conference. It also summarizes the key insights derived from RAND's scenario analysis and expert elicitation and includes abstracts of papers some of the panelists submitted.

RAND played the roles of conference convener, organizer, and integrator and compiled summaries of issues and comments. However, it should be noted that this report is not intended to reflect RAND's thinking on the subject of energy R&D but rather the views of the many participants in the E-Vision 2000 process.

This volume presents supplementary materials—conference papers and additional analyses—developed for the E-Vision 2000 Conference, October 11–13, 2000, in Washington, D.C.

The S&T Policy Institute

Originally created by Congress in 1991 as the Critical Technologies Institute and renamed in 1998, the Science and Technology Policy Institute is a federally funded research and development center sponsored by the National Science Foundation and managed by RAND. The Institute's mission is to help improve public policy by conducting objective, independent research and analysis on policy issues that involve science and technology. To this end, the Institute.

1. Supports the Office of Science and Technology Policy and other Executive Branch agencies, offices, and councils

2. Helps science and technology decisionmakers understand the likely consequences of their decisions and choose among alternative policies

3. Helps improve understanding in both the public and private sectors of the ways in which science and technology can better serve national objectives.

Science and Technology Policy Institute research focuses on problems of science and technology policy that involve multiple agencies. In carrying out its mission, the Institute consults broadly with representatives from private industry, institutions of higher education, and other nonprofit institutions.

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This particular application of the Delphi method failed to produce clear convergence around a limited set of issues. This was due in part to the qualitative nature of the responses. The question itself failed to stimulate "out of the box" thinking, but rather produced concerns consistent with the current debate. In the future, non-energy experts from a wide range of fields will be engaged in imagining different energy futures and associated R&D investments implicated by those possible scenarios.

The E-Vision 2000 Conference

The E-Vision 2000 Policy Forum was built around three expert panels and a final open session. The three main sessions included presented papers and panel discussions on the following issues:

- role of information technologies in shaping future energy needs
- factors shaping worker and student productivity in buildings and the relationship to energy use
- effects of applying a "systems" approach to current and future energy supply and demand practices.

Each panel session began with presentations of the relevant papers, followed by discussions from the floor. In addition, conference attendees who had expressed an interest in speaking were given an opportunity to do so on the last day of the conference. Finally, keynote speakers addressed the audience at various points on the issues EERE faced.[1]

[1]Conference transcripts are available online See http://www.rand.org/scitech/stpi/Evision/Transcripts/ for transcripts of all conference sessions.

Conference Papers on The Influence of Information Technologies on Energy Use

Information Technology Impacts on the U.S. Energy Demand Profile

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The growth of information technology (IT) and the internet may dramatically change society and the energy sector. Effective energy policies require sound research and development (R&D) to investigate these changes. This paper explains how viewing IT and energy in the context of a social system allows us to recognize that the indirect and unexpected effects of IT may dwarf the direct impacts on energy consumption. It also makes recommendations for the difficult task of divining the future of energy demand.

Prognosticating the future of energy use can be dangerous business because, as the old adage goes, "the forecast is always wrong," especially in an era of rapidly emerging and immature technologies (Fraser, 1998; de Neufville, 1990). IT is one of these emerging technologies and is ubiquitous enough to be involved in all sectors of energy use, including transportation, heating, electric power, construction, communication, and manufacturing. It promises to be the newest wave of "creative destruction" by causing business and societal upheaval and by creating openings for new goods, new methods of production, new transportation, and entirely new market and living scenarios (Schumpeter, 1942). Although precise predictions are likely to be inaccurate, it is still possible and advisable to establish a framework to evaluate the impact of IT on the US energy profile. To create this framework, this paper

- provides background on the IT-energy debate
- assesses of the state of relevant data.
- explains and exemplifies the nature of complex and counterintuitive system effects

[1]Note that the contents present the views of their authors, not necessarily those of the Department of Energy, RAND, or any other organization with which the authors may be affiliated.

- evaluates the substitution of IT for energy
- recommends a research plan

Background

Two major conflicting views exist on the effect of IT on the US energy demand profile. The first view states that the use of more electronic equipment will increase energy consumption and intensity. This school of thought argues that internet machinery constitutes an 8% share of US electricity demand and is likely to grow (Mills, 1999). The opposing school of thought attempts to use more realistic data in estimating that IT is replacing labor and energy as factors in US productivity, and thus drives down energy intensity (Romm, 2000). The views are mutually exclusive and based on significantly different data sources, but neither has enough facts to make reliable predictions.

In addition to these two major views, other work focuses on the link between IT and economic growth or concern themselves with the impact of electronics on the demand for reliability in electric power. These are clearly important issues, but are largely superseded by the larger question of how IT impacts electricity demand while simultaneously spurring enormous social changes and impacting energy use patterns.

Given these two conflicting views, the secondary energy and electricity concerns, and the prospect of social change, DOE faces three major issues in the face of proliferating IT. First, DOE can address the electric load due to electronic equipment. This is relatively simple to research but yields the least useful information regarding broad trends of the future. Second, DOE can address how increased dependence on electronics creates demand for more reliable power. Sensitive electronics may require improving the electric grid or changing the current generation framework. Both of these issues, however, are electricity-specific and limited to narrow economic sectors. The third area of interest is how IT affects social changes and how those social changes affect energy use across sectors and sources. These social factors become the underlying variable, and are also the most difficult to map.

Of these three major issues, energy use by electronic equipment is the most simple and least important. The internet and e-commerce have shown dramatic growth: over 250 million people are estimated to be on-line worldwide, with the numbers expected to grow to 350 million by 2005. Retail e-commerce in the US alone was conservatively estimated by the US Department of Commerce to be $5.3 billion in the fourth quarter of 1999, representing 0.64 percent of retail

purchases. Estimates of the electricity cost of all the electronic equipment used to make this happen, including computers, servers, routers, and switches, range from 1% to the previously mentioned 8% of US energy use (Matthews, 2000; Kawamoto, 2000). Although clear data for this is not yet available, it is reasonable to expect accurate estimates of the internet's electricity demands soon. These are reasonable research expectations because the average power consumption of computers and other electronic equipment is known and their aggregate quantities can be tallied. Given the limited range of the internet's electricity needs, the overall change in quantity is likely to be negligible relative to the broad energy demand changes promised by a developing internet society.

The second issue, electric reliability, is a growing concern as sensitive electronics become embedded in society. Complex electronic systems are considerably less tolerant of power fluctuations than light bulbs and other traditional electric devices; disturbances of even less than one cycle (1/60 of a second the US, 1/50 of a second in many other countries) can interfere with IT functionality. Three solutions present themselves to this problem. First, electronics may be designed to be less sensitive to power fluctuations with additional time and development. Second, additional generation systems and distributed generation may play more important roles in the electricity profile of the future. Finally, the US transmission and distribution grid may require significant investment and upgrading to ease congestion and ensure more reliable and higher quality power (Casazza, 2000) . Tradeoffs between these three choices involve cost differences, convenience, power quality, efficiency, and environmental effects. However, this field limits itself to the electric sector. Broader effects of IT can be seen by expanding the scope of investigation to societal effects and other energy sectors.

The third and most daunting of the challenges involves managing entire societal changes that will dramatically reshape the energy demand profile. Will telework decrease energy use in transportation and offices? If so, will those changes be moderated or counteracted by home and lifestyle energy use? In another field, will e-commerce and direct shipping reduce energy use in retail stores and inventory warehouses, and will those reductions be offset by increased energy consumption in distribution and packaging? How energy intensive will people's lives be in an online world? Given today's tools and knowledge, it is impossible to predict accurately these long-term and overall societal effects of internet use. The best we can do is establish a framework and plan for assessing these changes. This socio-economic-energy system is the primary focus of this paper.

The State of Relevant Data

The challenges of societal change are made more difficult by the lack of accurate data. Metrics are unclear as we make predictions about an online age. Some metrics, such as overall energy demand or energy consumption per mile of object transported, are likely to remain constant. Other metrics, such as electricity use per megabyte of information transferred, are relatively new. Even given clear metrics, data is lacking. There is a dearth of definitive data on internet use, and even less information on energy consumption due to this use or energy consumed per unit of information transferred

Data so far are insufficient. Even the simple electricity demand of all internet-related electronic equipment is not accurately assessed yet, and it is only one small part of the overall system. Assessments to date are inaccurate because some studies have exaggerated the power consumption of electronics in claiming that the internet is fundamentally fueled by coal (Mills, 1999). Other studies have more reasonable data, but have them only for short periods of time and by their own admission do not yet credibly reflect established energy intensity trends. (Romm, 2000) Data is also not calibrated, with different studies examining different energy forms; some examine broad energy patterns while others restrict their views to electricity use in the commercial sector.

To the credit of researchers, IT and e-commerce data is not easy to uncover and clarify. Take, for example, the difficulty encountered in just one small subsystem within the overall e-commerce issue: online music. This is an ideal IT subsystem for study because of its transformative social popularity, potentially vast economic consequences, and lack of credible data despite tremendous attention. It has major economic and societal implications and is under heavy scrutiny, yet even here clear data is difficult to discern and the future of this issue is unpredictable. Napster, a files-trading program and eponymous company, is the target of a lawsuit by major record companies concerned about the frequent pirating of copyrighted music. Napster maintains that it provides a legal service and that illegal transfers of music files are not significantly detrimental to music distributors and companies. Record labels claim that CD sales are dropping as a direct result of increased Napster use. Yet the data conflict. One side points to reports that consumers are "swamping" music stores and that the three fastest-selling albums in music history have all appeared in the past year. Another side cites reports that the "swapping of computer files [is] affecting disc sales," by reducing sales by up to 4% near college campuses where Napster is most frequently used (Lamb, 2000; Learmonth, 2000). Both sources of data are contested by opponents for being inaccurate or misleading. There is no consensus yet.

If a small subsystem under as much scrutiny as music-trading creates so much disarray in relatively simple data, then the overall changes in society due to internet proliferation are clearly beyond simple measure. Music is merely an early indicator of future net debates because its format and information quantity allow for easy transfer over today's internet connections; similar issues will arise in other media later. Whether this issue is called "the canary down the digital mineshaft" or "the tip of a far bigger iceberg, the implication is clear that this is just a small part of a larger system (Economist 2000, 10/5, 6/22). But even here internet data is lacking.

From the musical microcosm to the overall internet, there is still no accurate metric for the amount of information transferred, much less the energy used in doing so. Simple results from small subsystems, such as fuel saved due to telecommuting, remains unclear. Meanwhile, reliable estimates of per-capita energy intensity remain a dream in the rapidly-growing internet society.

It is encouraging that attention is being devoted to the long-term impacts of IT on energy demand. Although data is lacking, basic information and an intelligent framework for thinking about energy challenges may keep the future from surprising us too badly. We currently do not know enough about the internet, or even its basic building blocks. Achieving accurate data even of present trends is a laudable goal. However, most changes occur because of societal changes resulting from new technology. We do have frameworks for social change, and should analyze this case within this larger arena.

Complexity and Counterintuitive System Effects

The introduction of IT to society results in a complex system with such a wide array of possibilities that it is difficult to identify specific cause-and-effect relationships resulting from its use. We do not know, for example, whether telecommuters use less energy at home than they do at offices, or even if they use less fuel in driving for their new lifestyles. We do not know whether improved communication via IT will increase or decrease the desire for personal mobility. We also do not know whether the energy savings from having virtual, online stores mitigate the extra energy used in packaging and shipping products to consumers. Although some data exists on these subjects, it is not comprehensive and especially weak if we were to extrapolate across societies and cultures.

These examples are all indicative of a complex system, one in which linear predictions and solutions are unlikely to work. Indeed, trying to view the IT-energy system piece-by-piece will lead to myopia and missed avenues. A holistic

systems view is the best way to address the issue, although this is by nature interdisciplinary and difficult for a single agency to handle.

Myopia in Action: Office Equipment

One extended example of a piecemeal, rather than system approach, can be seen in debates over office equipment. One estimate of total power use by office equipment and network equipment is about 74 Twh per year, or about 2% of the total electricity use in the US (Kawamoto, 2000). Within the business world alone, the EPA estimates that office equipment accounts for 7% of commercial electricity used and maintains that "office equipment, computers in particular, is the fastest-growing source of electricity consumption in businesses and homes" (S.F. Chronicle, 2000).

This sensationalist approach to the electric load of office equipment has the odd effect of masking an even larger sensation: the broader energy effects of the use of electronic equipment. Computers and IT equipment do represent additional energy load, but predictions of resulting surges in electricity demand have been dampened by increased efficiencies, technology advances, manufacturing reductions, and social changes (Harris & Crawley, 2000).

Computer equipment can lead to energy consumption effects orders of magnitude higher than the energy consumption of the equipment itself. A networking card, for example, might require 200 milliwatts, or 4.8 W-hr per day, to operate its internal circuitry. However, the use of the networking card could cause its owner to leave his or her 50 W computer in constant operation, thus leading to a load of 1.2 kW-hrs per day.[2] Thus, the card's impact on the energy consumption of the computer can be 250 times greater than the consumption of the card itself.

Thinking about the card's broader effects on energy use, the same owner may choose to telecommute instead of driving to work each day. One gallon of gasoline could be saved in a 30 mile round trip. The chemical energy in the gasoline, 125 MJ, could be used to generate approximately 11.5 kW-hrs of electricity. This is almost 10 times the energy used to keep the computer on continuously and almost 2400 times the energy consumed by the networking card itself. Clearly, the effect of individual pieces of electronic equipment on the

[2]50 watts may be a conservative average figure for computer energy consumption, but also includes part-time monitor use. The EPA estimates that a typical desktop computer uses about 45 watts and a monitor an additional 110 watts. Dell, the largest PC vendor in the United States, figures an average of about 40 watts for its PCs and 70 to 80 watts for a 17-inch monitor. The monitor, however, may switch into an energy-saving mode more often.

energy consumption of a society can be tremendous and considerably larger than the integral of the power flows into those devices. One must consider how the equipment is used, what other energy flows are involved or negated, and how the device affects the manner in which people work and live (Sullivan, 1994). Unfortunately, the borders of the complex system we are contemplating are large: the previous example could have potentially included home heating, server energy use, other car trips, or even a fraction of the energy used in manufacturing and disposing of the car and computer.

Pursuit of these complex systems may initially seem like a fool's folly, but complex systems analysis is eminently possible. Societal effects can sometimes be modeled as an complex engineering system. Part of understanding why this modeling is achievable lies in understanding a systems approach to problem-solving.

IT in the Context of Systems Analysis

The introduction of IT can be easily viewed as a systems challenge. Several systems sciences have been developed in the last half-century to handle difficult input-output questions with many variables, actors, feedback loops, and uncertain consequences. These schools of thought include complex systems analysis and earth systems engineering and management, both of which can be helpful in assessing IT.

Classic science was essentially concerned with two-variable problems: one way causal trains with one cause and one effect or with a few variables at most. The classical example is mechanics. It gives perfect solutions for the attraction between two celestial bodies, a sun and a planet, and thus permits exact prediction of future constellations and even the existence of still undetected planets. However, even a "simple" three-body problem of mechanics no longer allows for a closed solution by the analytical methods of mechanics and can only be approached by approximations (von Bertalanffy, 1969). Given the relative simplicity of three-body mechanical problems, it is readily understandable that complex effects of IT on society must be viewed from a broad, systems-oriented perspective. Like the civil rights movement and the breakup of the Soviet Union, the introduction of IT represents the edge of chaos, that is, the balance point between order and chaos in a complex system and where new ideas and innovation are nibbling away at the edges of the status quo (Waldrop, 1992).

Complex systems belie their name because despite their holistic nature, they can still be disassembled into three elements. The first elements are components, which are operating parts consisting of inputs, processes, and outputs.

Individual IT capabilities are components, as are human reactions and production processes. Each component then has attributes, which are properties or manifestations of the components. Attributes may include such disparate examples as energy consumption levels or desire to travel. Finally relationships are the elements that link components and attributes. These include the complicated cause-and-effect feedback loops and tradeoffs that describe, for example, how IT changes in one sector can affect fuel consumption in another (Blanchard and Fabrycky, 1981). These complex social systems may be daunting, but their analyses are necessary in order to understand the impacts of IT on energy.

Technology and Socioeconomic Interaction

Viewing IT and energy as part of a complex system allows us to recognize that the indirect effects of IT may dwarf the direct impacts on energy consumption. These second order effects are tremendous socioeconomic changes—termed "second" order in this paper only because they are links between IT and massive energy demand changes. They are not of second order importance; instead, socioeconomic links lend added measures of complexity—and understanding—to the introduction of new technologies. This section explains how IT can force social changes, but then again how well-understood and predictable social patterns may then help shape the energy effects of IT.

IT can cause revolutionary social changes in the same way that other major technologies have changed the pattern of life. Automobiles, for example, became so ingrained in American society that they have molded US socioeconomics. They have become ubiquitous and affected nearly every aspect of American life, including which industries are largest, where we choose to live, and what our cities, suburbs, and nation look like. Technology can even change major societal definitions and attitudes, as witnessed by how automobiles altered basic premises of freedom by incorporating mobility into the definition.

Cars became a symbol for freedom, with mobility acting as an important linking factor between automotive technology and the freedom whose definition transformed as a result. It is possible that IT may also become a vehicle for freedom if personal access and virtual mobility rise in importance in this arena. However, the important lesson from internal combustion technology is that its introduction alone did not directly create a world virtually dependent on petroleum. Rather the second-order socially-developed need for freedom and mobility did, demonstrating how technology can help shape social entire socioeconomic patterns.

If technologies can forge and trace socioeconomic patterns, then the reverse can also be true: understandings of socioeconomics can help predict technological trends. Social and economic changes in the US sometimes do follow distinct stages of development that can be measured and modeled and therefore framed and predicted. Even social and economic upheavals can sometimes lead to predictable outcomes and transition patterns (Schumpeter, 1942). These frameworks allow us to draw some parallels in between IT and economic trends. Specifically, the IT-energy framework may follow a broad trend of US industrial-economic developments.

A parallel can be drawn between IT and the development of American socio-economic phases. The US, like many other countries, followed a typical socio-economic path. It started as a primarily agrarian economy that developed with the industrial revolution into a more manufacturing-dependent and urban system. More recently, the US has shifted from an industrial to a more service-intensive economy. The US is not alone in this shift, and now some less developed countries are following similar transformations from agrarian to industrial or even service economies.

IT parallels a service economy because it is the latest stage of economic progression and can also add value to a process even when no manufacturing occurs. This is because both IT and service industries rely on a knowledge economy, with knowledge as the key scarce resource instead of capital or labor. Like service economies, IT promises, albeit without guarantees or proof yet, to be less energy intensive than heavy manufacturing and construction.

The link between poorly-understood technologies and well-understood socioeconomic patterns suggests that technology metering and road-mapping activities can be useful strategies for understanding technology trends and their connections with economic growth. Similarly, economic road-mapping can shed light on the integration and future of new technologies. As recommended by previous scientific and government panels, these societal and technological road-mapping activities should be continued by government with expanded efforts to share perspectives across fields and sectors (NRC, 1999).

Examples of the Complex and Counterintuitive Effects

History is littered with the corpses of predictions and conventional wisdom gone awry in the wake of society-shifting new technologies. These upcoming examples serve to illustrate not the futility of prediction, but rather the importance of including as many features as possible for fear of leaving out critical factors.

An earlier example in this paper dealt with Napster and the proliferation of on-line music trading. Yet this is similar in some ways to the popularization of music on radio. The free broadcast of music by radio was initially perceived by the music industry as a threat. In fact, the opposite was true because radio played a large role in the popularization and sale of music albums. This marketing factor had not been considered, yet it led to a new system by which consumers heard the product for free before purchasing new music albums. The exclusion of this feature from the system model lead to an entirely erroneous prediction.

The popularization of phones in the 19th and early 20th centuries was predicted by some to lead to less travel due to improved communication. Here again, the expected cause and effect relationship failed to materialize. The missing factor this time was that people made more personal and business contact over large distances and thus demanded more travel instead of less. A more recent research trend anecdotally views transport and telecommunications systems to be synergistic and focuses on how increases in email correspond with air transport.

While the above two examples were predictions at complete odds with reality because of missing factors, there are many complex systems hypotheses which are partially right. One example comes from paper. Since paper is very energy intensive to produce, any reductions in paper due to IT could be very important to the overall US energy profile. Popular predictions for paperless offices during the computer revolution appeared doomed to failure for the past two decades. During that time, office demand for paper has increased significantly alongside the rise of workplace computers (Cusomano, 2000). What was missing from systems calculations? The ability to effectively transfer information in the correct medium. People still wanted to read reports on real paper. The reduction of paper is finally beginning to occur not with reading material, but rather with the elimination of entire paper chains in e-commerce. AT&T estimates indicate, for example, that some 15 million pages of paper use per month have been eliminated by going to paperless, internet-based, billing systems for AT&T customers. On the business-to-business side, AT&T will eliminate the use of over 1.5 million pages of paper per year by going to e-commerce links with just one major supplier. According to a study by the Boston Consulting Group, the internet will reduce the demand for paper by approximately 2.7 million tons by 2003, a full 20 years after the enthusiastic paper prognosticating began. Anecdotal data suggests demand of paper per unit of information appears to be decreasing.

How Converging System Components Cause Unexpected Interactions

Proper systems analysis requires consideration of all the components in a system, but these components are not always easy to identify. One example of this difficulty can be seen in the power industry itself. This section examines the unusual path of gas turbine technology, which surprised many by revolutionizing the power market almost as radically as IT may revolutionize society and energy demand.

Gas turbines are now a common and expanding form of electricity generation in the $220 million US power market, but many would not have foreseen this leap one generation ago. These machines are fundamentally different from their steam turbine predecessors in terms of engineering, thermodynamic cycle, environmental output, economics, operation, and social impact. As in IT, the footprint of this technology is considerably larger than the technology alone; it is argued that the technology allowed for a whole new way of doing business in the generation market, thus leading to power deregulation, industry restructuring and radical consumer and social choice in the power industry (Unger, 2000).

Perhaps not surprisingly, the causes of this minor revolution are numerous. To predict the outcome, one would have to know about all of the factors—a critical part of complex systems analysis. In the case of gas turbine technology, there were four major system components, or causes, which helped usher in the new era and fundamentally change an entire industry network (DOE, 1998). These four components included specific technological developments, fuel availability and policy, environmental regulations, and consumer choices. Individually, the forces would not have led to the revolutionary consequence, but change occurred when the four forces converged.

The first component, technological developments in gas turbines, included both predictable improvements and radical changes. Predictable improvements, such as the iterative substitution of metal alloys to allow for higher operating temperatures and improved efficiencies, were numerous throughout the second half of the 20th century. These improvements were almost expected as a matter of course. However, a technological leap occurred with the introduction of cooling systems in the 1960s, which proved to be the catalyst for great increases in temperatures and operating efficiencies. Some engineers would have been able to predict this step-function, but it took many by surprise (Unger, 2000). However, technological improvement alone would not lead to major change.

The second component was a series of laws regarding the availability and use of natural gas. Natural gas is the primary fuel for gas turbines, and this fossil fuel underwent dramatic cost increases during the energy crises of the 1970s. Furthermore, perceived shortages led to the federal Fuel Use Act of 1978, which put a virtual moratorium on the installation of many new gas turbines. Utilities turned to traditional, cheap, coal-fired steam power plants to serve electricity generation needs. This action was a clear signal to turbine manufacturers to reduce effort towards gas turbines, since the future of the technology was significantly jeopardized. Later, beginning during the mid-1980s, the shocks of gas deregulation ended, new gas resources were discovered, complementary industries (such as the gas pipeline and distribution business) had developed further, and gas prices fell back to competitive levels, spurring the market once again. The Fuel Use Act was rescinded and the gates were once again open for the pursuit and introduction of new turbomachinery.

The third component that contributed to the turbine technology revolution was a series of environmental regulations. Tough new anti-pollution laws, including the Clean Air Act and its subsequent amendments, heaped new costs (of externalities) on traditional coal power plants and provided a competitive advantage to gas turbines because of their relatively clean-burning fuel. Thus, environmental policy helped to promote a new era of power production and consumption.

The fourth component that led to industry and social changes was electric deregulation and the introduction of competition to the electric power industry. The Energy Policy Act of 1992 and state level competition-promoting electric regulatory changes, helped to spur renewed interest in and sales of gas turbines in the 1990s. This is because gas turbines are smaller and more modular than traditional steam turbines, thus representing smaller capital investments and quicker rates of return in a power industry that suddenly must care about its profitability in a new, competitive age.

These four components involved many actors, including manufacturers, generators, regulators, and the public. The components also acted as both causes and effects, with complicated interactions and feedbacks between them. Individually they would not have led to major societal or industrial changes, but their interaction and system relationships led to a major restructuring. Furthermore, each of the components would have been difficult to predict, and would only have been forecast by experts in the individual fields. Those experts would not have been able to reach the same conclusions about the other, disparate components, and thus would not (and did not) forecast the fundamental changes to come.

Of course, IT also impacts the power generation field, but the important relationship here is how both information technology and turbine technology can have complex systems effects far beyond what initially appears. Furthermore, critical system analysis requires examining all the converging components and network effects, even though some may appear distant or unimportant. This example did so in hindsight, but a similar framework can also work for predictions. Also, this example demonstrates that identifying individual components is a critical step in identifying relationships in a system. The same must be done for IT and energy.

The Substitution of IT for Energy

We would ideally like to manage the complex and societal changes heading our way due to IT, but from an energy perspective, what do these changes mean for the US energy demand profile? Simple first order effects may include increases in electricity demand in certain areas and the need for more reliable energy grids to supply electricity to sensitive electronic components. However, the last two sections of this paper demonstrate that the largest effects may be second order or system effects resulting from IT-induced societal changes. This fundamentally means that societal changes may facilitate the de facto substitution of IT for labor and energy.

This section examines five ways in which the substitution of IT for energy may occur. First, IT may offset the need for energy consumption via telework. Second, the substitution may be seen in "virtual" stores and e-commerce, exemplified by Amazon books and HomeRuns.com. Third, IT might reduce energy consumption in conventional stores by streamlining product inventory, distribution and sales cycles, thus reducing waste and increasing efficiency. Fourth, IT may help create more intelligent buildings and machines which may operate more efficiently. Finally, IT can lead to dematerialization of goods, thus saving the energy of those goods' production and distribution.

Telework

Telework offers the possibility of energy demand changes by allowing people to avoid having to commute to an office. One telework energy example was examined earlier in this paper in a simplified two-variable comparison between the energy use of a networking card and the energy saved through not driving. Although our understanding of the social and environmental dimensions of some service areas such as telework is improving, we are far from understanding the social, environmental and cultural impacts of information infrastructure, and

the services it enables. Nevertheless, telework is increasingly recognized as an important "triple bottom line" technology in many companies. It benefits firms economically, because they save on rent and can retain valuable employees, and because teleworking employees are generally more productive. It provides social benefits because employees and their families enjoy a higher quality of life. Moreover, traffic congestion, a major problem in many urban and suburban areas, is reduced, which benefits everyone who uses the roads. It provides energy and environmental benefits because fuel use and emissions are reduced if unnecessary commuting is limited (Allenby and Richards, 1999; FIND/SVP, 1997).

The data underlying these telework conclusions are sparse and incomplete to some degree, and the extent to which societal patterns will change over time in unpredictable ways must be considered in any comprehensive cost/benefit assessment. Thus, a systems approach might lead one to ask whether in the longer term the availability of internet infrastructure, combined with the delinking of place with work, might not lead to completely different patterns of energy use with corresponding implications for demand for products (enhanced e-commerce); transportation systems (more dispersed populations requiring greater private transport); and impacts on the breadth and vitality of urban centers. Again, IT makes telework possible, which in turn creates social changes. The social changes, though still unclear, promise further changes in the US energy profile.

E-Commerce

IT can also change the energy demand profile by potentially replacing conventional, or meatspace, stores with cyberspace e-commerce. E-commerce may lead to some substitution of IT for energy, but may also create some additional energy needs. Once again, a systems approach is necessary to assess the likely overall impact. The analytical difficulties of the complex e-commerce scenario become notably acute given how e-commerce has exploded in recent years (Bodman, 1999). Here, there are no analytical structures or methodologies by which to begin evaluating the energy implications of such a complex phenomenon (Cohen, 1999; Rejeski, 1999). Nevertheless, the outlines of a framework can be seen in several examples.

Two examples of common on-line purchases can be seen with food and books. In the book business, Amazon began a trend by selling books through its website. Conventional bookseller Barnes and Noble responded by establishing its own e-commerce capabilities, while both companies also compete with other online

retailers of related products, such as Pennsylvania-based music retailer CDNow. In the food business, companies such as HomeRuns.com compete against traditional supermarkets and local grocers by offering online purchases followed by home delivery. In all of these cases, websites vie against concrete-and-glass stores—and against each other—as areas of browsing and purchase. The simplest of energy analyses would compare the energy use of a website with the energy use of a meatspace store, yet even this is difficult. Anecdotally, the website requires a small fraction of the energy (almost all in the form of electricity) to operate in comparison to a store, which requires a variety of energy forms for heating, lighting and operation. A more comprehensive analysis would compare the energy used in the construction of a computer server to the energy consumed in construction of a retail store—or the energy saved in not constructing the retail store at all. Proceeding further, a full life-cycle analysis would include the (upstream) changed inventory structure of the store and the (downstream) differences in energy consumption if personal travel to stores for purchases yields to the individual packaging of goods followed by air-and-truck distribution to individual customers' homes. Although this energy-intensive distribution is indirectly caused by IT, energy expenditure may also be reduced by improved distributing routing algorithms and mitigated by a reduction in personal travel to retrieve purchases. Finally, a systemic study could also include the changes in land-use patterns and the dispersion of population that may occur if remote living becomes easier. The energy implications of such large social changes are tremendous, but will not be clear without additional study and systemic comparisons.

E-commerce is not limited to website versus store comparisons. IT can also reduce energy consumption in conventional stores by streamlining distribution, sales cycles, and business to business (B2B) marketing models, thus reducing waste and increasing efficiency (Kumar and Kromer, 2000). Consider Home Depot, which has shifted from simply selling home and construction equipment to small contractors—its most important customer segment—to offering a purchase sizing service. Contractors can log in to enter details of their job and Home Depot software then calculates what they will need and arranges for just-in-time delivery to the job site, eliminating the usual industry practice of over-estimating materials, which then get wasted. What's ordered gets used as a result of a more efficient, IT-aided process (Allenby, 2000).

Intelligent Systems

IT can also change the energy demand profile by creating intelligent or responsive control systems that can optimize energy use in buildings and

machines. Examples abound, but the fundamental driver is cost-saving. Sometimes this economic efficiency leads to energy efficiency also, but it should be noted that one does not always lead to another.

The most heralded example of intelligent IT energy systems, that of electric metering in a deregulated market, offers the promise of selective purchases so that consumers can respond to real-time electric pricing. This allows consumers to reduce their demand (within limits) during price peaks by identifying the peaks through IT and then adjusting their building or factory controls correspondingly. The cost advantages for this system are clear, especially if consumers have flexibility in the time of their demand. The overall energy advantages, however, are more complicated. Delayed electric demand may not mean a change in aggregate demand over longer periods if conservation is limited to narrow time windows.

The ability to "game" electric prices, could impact energy demand more profoundly if the energy profile of electricity generation changes as a result. This can happen in two ways. First, price peaks usually induce generating companies to increase their supply and gain additional revenue while prices are high. To do this, they start running their most expensive, frequently least-energy-efficient equipment. If IT systems can cause consumers to shave these price peaks, the bursts of inefficient generation may fall also, thus reducing the fuel demands of generating companies. The caveat to this is that the advantages of load-leveling are independent of aggregate improvements power plant efficiency. High electricity prices do not have a standardized effect on efficiency; rather, the effects depend primarily on the supply profile and status of generator competition.

The second way in which intelligent IT metering could affect the energy profile is that it can facilitate and buttress discretionary electric supply choice. Consumers in several states, for example, have the option of selecting their choice of generation companies. Although the contract path of electricity does not remotely match the actual electron path from generators to consumers, it is possible to "select" alternate generation technologies such as biomass, solar, or wind. Electricity is more expensive from these sources than from traditional coal- and gas-fired power plants, but a thriving green power market is facilitated when consumers can make environmental choices while being spared the pain of price peaks mentioned earlier.

Of course, electric metering is only one example of intelligent IT energy systems. Other examples, such as building thermostats, may have nothing to do with electricity and may save fossil fuels directly instead. However, all these systems

revolve around cost savings. Whether these cost savings convert to higher energy efficiencies depends on the systems.

Dematerialization

In the Amazon, Barnes and Noble, and HomeRuns.com examples earlier, stores are "dematerialized" into the realm of IT, but products remain real and solid. This section deals with how IT can dematerialize goods as well as stores, and the energy impacts of these changes. Unlike the case before, where changes in the very existence of buildings can lead to enormous social, mobility, and housing dispersal choices, here the immediate effects can be as important as second order impacts.

Dematerialization allows items that are primarily based on information to remain in electronic form. Thus, items that are constituted of information or intellectual property, such as printed specifications or forms, audiovisual material and books, are prime candidates for dematerialization. Any of these items or products can be digitized and electronically transmitted instead of printed, packaged, or physically placed on any solid medium. With no packaging or manufacturing, energy consumption goes down per unit product.

Earlier, the music industry and Napster were used as examples of poor and conflicting data. Here, we use the same area to illustrate a fundamental material and social change as a result of IT. The electronic transfer of music files threatens not only those who seek revenue for intellectual property, but those who make the hardware necessary for carrying that property. CDs themselves become extraneous. The energy savings of not manufacturing them can extend up the product life cycle to include metal mining energy, smelting energy, factory production energy, and packaging and distribution energy. The same is true for the petroleum plastics in videotapes no longer necessary and pulp in newspapers and books no longer printed.

Dematerialization can also apply to inventory waste, but with a slightly different definition of dematerialization so as to include the elimination of the need for inventory. One example of this can be seen in Dell Computers. The usual practice in the computer industry is to maintain a 60 to 80 day average inventory. Especially given the rapid pace of technological evolution in that industry, that translates into a lot of inventory that never gets sold, thus becoming waste (and the warehouse space and transportation systems that are used, as well as the manufacturing impacts embedded in the product, are also wasted). Dell, on the other hand, uses its e-commerce systems, both upstream and downstream, to operate on about 6 days of inventory. This e-commerce system has created a

profound shift in the economics of Dell's operations: in 1990, Dell had sales of $546M and required $126M in net operating assets to run its business. By 1998, however, Dell had $18.2B in sales using only $493M in net operating assets. Operating assets as a percent of sales declined from 23% to 3%, while return on invested capital was up from 36% in 1990 to over 400% in 1998 (Bodman, 1999). In short, as in the case of energy consumption per unit economic activity, anecdotal evidence suggests that the Internet could be a powerful dematerialization technology (Allenby, 2000).

Framing Efficiency

As demonstrated, IT may affect energy consumption in both direct and indirect ways. It consumes electricity directly, although this is only a small fraction of the overall energy influence. It also makes fundamental shifts in production and society that prevent some products from even being manufactured and changes the way other goods are transported, thus affecting energy consumption. However, many of the illustrations of the previous section actually deal with improving the energy efficiencies of entire processes or product chains, such as saving energy not used in retail sales and unnecessary inventories. This raises an interesting question of the value of pursuing efficiency alone.

A focus on how IT increases energy efficiency may lead to an ideological problem. Although increasing energy efficiency is a worthwhile interim goal, it may not achieve longer term objectives of a genuinely sustainable energy future. Here, we may benefit from a review of a similar situation of a technological revolution in England's history. Like IT, the introduction of the steam engine prompted widespread societal growth while promising efficiency and decreased energy intensity.

England began the 18th century with the Savery steam engine, a crude and inefficient forerunner of the more successful and celebrated machine devised 67 years later by the Scottish engineer James Watt. The Savery engine was nevertheless the state-of-the-art machine in the first part of the 1700's, helping England become the leading industrial power in the world. England burned great quantities of its coal reserves, prompting some fears that the nation's coal seams would someday be "emptied to the bottom and swept clean like a coal-cellar." Many of these fears dissipated with the introduction of the Watt engine, which ran almost 20 times more efficiently than the Savery version. When the Watt engine was put into wide service, coal consumption initially diminished by one-third. However, history showed that the market entrance of the new and efficient engine eventually prompted demand for coal to rise tenfold. It was the

flip side of the Savery scenario—far greater energy efficiency made engines much less expensive to run, which led to an extraordinary increase in the use of coal and a net increase in energy consumption (Inhaber, 1994).

The steam engine example may parallel some aspects of IT introduction. Many of the examples of IT cited above, including dematerialization, intelligent systems, and some aspects of e-commerce, are potential improvements in efficiency alone. The short term and long term implications of these improvements are still unclear. IT efficiency may not be the end goal from a DOE perspective. As the Savery example demonstrates, cumulative long-term effects are also important.

Recent data do show improving trends in national energy efficiency, and the examples above show how IT can contribute to energy efficiency, but we are unable to attribute the national trend to IT yet. More definitive proof is necessary to establish this link.

Conclusions and Recommendations

There is good reason to believe that IT is a revolutionary phenomenon that is already reshaping US energy needs. Although IT relates directly to the energy sector through its own electric demand and need for reliability, IT's overall impacts on energy demand are dominated by indirect and complex socioeconomic system effects.

Accurate data on a variety of fronts is scarce, leading to several competing views of IT's impact on energy demand. The simple comparisons of office equipment energy use are a useful first step, but the systemic and social impacts of IT reach far beyond what is currently being studied. The greater effects of IT may include land use changes, a greater dependence on electronics, increases or decreases in personal mobility and travel, a reduction of waste through IT efficiency, and the dematerialization of some goods. Complex systems analysis of these interactions is challenging, but it is feasible and necessary to discover how IT interacts with socioeconomic forces and, in turn, affects energy demand profiles across sectors. There are several tools and system frameworks at our disposal, including relatively well-understood economic patterns that make social and technological roadmapping possible.

Table 1 summarizes the research needs identified in this paper. Combined, they form a research plan which DOE can implement in an effort to manage and predict how IT will impact the US energy demand profile. The nature of complex systems dictate that most of these research areas are interdisciplinary

Table 1

Information Technology Research Needs

Area or Concern	Research Need
Direct Links Between Information Technology and Energy	
Electric load of IT equipment	Standardized metrics (energy/unit of data transfer)
	Credible basic and aggregate data on energy use
Electric reliability	Research on the desensitization of IT equipment to short electric fluctuations
	Optimization of investments enhancing existing transmission and distribution grid
	Analysis of competitive and independent system operator effects on electric reliability
	Projection of reliability impacts and costs of distributed generation
Indirect, Societal, and Complex System Links Between IT and Energy[a]	
Socioeconomic and energy impacts of IT[b]	Technology and socio-economic roadmapping
	Identification of IT, socioeconomic, and energy system components (including elements, attributes, and relationships)
	Identification of IT correlations with sectoral switch to service-based economy
	Substitution of knowledge for capital and labor
	Long term vs. short term value of incremental increases in energy efficiency
	Long-term analysis of correlation of decreasing energy intensity and the rise of IT
Telework	Balance of energy costs and benefits of telework on several levels
	Simple comparison of energy equipment use
	Comprehensive life cycle analysis including equipment construction and disposal energy
	Complex system analysis of resulting changes in land use patterns, traffic patterns, travel preferences, fuel use, and energy demand
E-commerce	Simple analysis (Conventional store energy consumption vs. website energy consumption)
	Life cycle analysis (Conventional store construction and disposal vs. server construction and disposal)
	Systems analysis (Customer driving energy vs. goods packaging and delivery energy)
	Complex social systems analysis (Changes in land use or population dispersion)
	Energy impacts of waste reduction and B2B efficiency gains

Table 1—Continued

Area or Concern	Research Need
Intelligent systems	Effects of electric gaming on retail electric generation choice and fuel use (i.e. green power)
Dematerialization	Life cycle energy savings and aggregate quantities of material not produced
	Inventory (i.e., Dell)
	Goods (i.e., CDs, paper)
	Paper (i.e., AT&T)
	Survey personal preferences (Do people want dematerialized goods?)
	Transition costs (Social cost and effects of companies left behind wave of creative destruction)

[a]Potential substitution of IT for energy.

[b]Analysis of general complex systems interactions.

and do not fall into traditional agency research categories. Many components of analysis span issues of commerce, energy, labor, and social desire. Complexity and breadth are not valid excuses to avoid studying these systems. We have proven abilities to tackle systems analysis, and they must be applied to IT and energy as well.

Our success at energy planning and management depends on making reasonable projections. Our frequent inability to understand the future except in terms of the past is a limitation that becomes especially apparent during times of rapid technological evolution. Despite this handicap, we now have tools and a framework for analyzing the impacts of IT on the US energy profile.

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Competitive Electricity Markets and Innovative Technologies: Hourly Pricing Can Pave the Way for the Introduction of Technology and Innovation

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For most electricity consumers, the transition to a "competitive market" has been unremarkable—if noticed at all—because the transition has come almost entirely at the wholesale level, where few consumers are involved. Not much (and, from my perspective, not enough) has changed in the retail market for electricity or in the consumer's understanding of electricity services to make for effective competition. As an early proponent of a competitive retail electricity market, Sempra Energy is urging the adoption of at least one step we believe will enhance competition significantly: the imposition of hourly retail electricity prices. This is an essential step to create competition in the retail end of the electricity market and, ultimately, more effective competition throughout the electricity sector. This market reform will have the added benefits of speeding the development and introduction of new technologies that can transform the electricity industry and spurring innovative new products and services.

The Department of Energy should keep in mind the compelling link between public policy and new technology. Retail competition in the domestic electricity industry will have the long-term effects of reducing prices, increasing the range of products and services available to consumers, and improving the overall delivery system. But those benefits cannot be achieved without the addition of an essential element of a competitive market: presenting accurate price signals through the use of hourly prices reflecting wholesale price fluctuations in the broader regional commodity markets for electricity. The hourly pricing of electricity at the retail level should induce many customers to reduce on-peak consumption, bringing pressure on suppliers to drop prices. Furthermore, exposing peak prices to customer choice can also spur the development and

[1]Note that the contents present the views of their authors, not necessarily those of the Department of Energy, RAND, or any other organization with which the authors may be affiliated.

introduction of smart services and alternative products. If consumers respond to high peak prices by reducing peak-period consumption or by trying new products and services, reliability will improve as electric transmission and distribution system operating margins are increased. If demand reductions and/or price reductions are sustained, environmental benefits can be captured as inefficient and dirty generating plants are forced into retirement. And, where automated meter-reading systems are deployed to facilitate hourly pricing, local distribution companies will improve their outage management capabilities as these systems also deliver high-resolution, real-time system information to operators. Sempra Energy encourages the Department to endorse policies incorporating the accurate portrayal of electricity prices to consumers and lay the foundation for and support the development of emerging energy technologies that take advantage of market conditions fostered by those policies.

Wholesale Market Volatility

As industry insiders and analysts know, the value of electricity is highly volatile. Prices in wholesale electricity markets vary hour-to-hour across each and every day, influenced by system loads, costs of production, the availability of transmission capacity, operating conditions on the local distribution system, and other market conditions As electricity demand reaches its daily peak, these factors combine to increase wholesale prices until demand abates, usually in the early evening, and prices fall back. During extreme peaks, prices can race skyward, particularly when some unique but not necessarily unpredictable influence, e.g., a plant outage, transmission constraint or extreme weather condition, enters the picture. Normal daily wholesale-price fluctuations may range from lows of under twenty dollars per megawatt-hour to fifty dollars at peak. But summer peak prices ten to twenty times "normal" are becoming common, with occasional nightmarish prices of over $5000 per megawatt-hour having been reported in several regional markets in recent years. A recent study by the Electric Power Research Institute indicates that electricity represents the most volatile commodity being traded today, with price risks several orders of magnitudes greater than for foodstuffs, equity and debt instruments, or any other energy commodity.

Retail Electricity Prices: Hiding the Story

At the retail end of the market, consumers, including those customers who currently procure their own electricity supplies, are insulated from and largely oblivious to the nature of the wholesale market and its daily perturbations. In the

first place, no regulatory jurisdiction has required hourly electricity pricing at the retail level. The thought of having every consumer, especially residential customers, receiving multipage bills detailing their usage across the twenty-four hours for each day of the billing cycle conjures up daunting public-relations issues. Thus, retail electricity customers continue to see monthly weighted-average supply prices in their bills. Price-averaging, a holdover from pre-competitive, regulated days when electricity was fully bundled, smoothes out and masks daily price fluctuations, including extreme prices. This situation breeds the problems evidenced in California this past summer. Where peak-period wholesale prices remain high across several days or weeks, consumers, completely unaware that their consumption contributes to the amplitude of both overall system demand and wholesale prices, receive monthly billings well above their expectations. Even worse, they receive the bad news too long after the fact, without any recourse or opportunity to adjust their usage levels. The absence of meaningful demand-side responses to prices constitutes a major impediment to achieving optimal competitive market conditions. And, as discussed in greater detail below, average pricing, with its lack of detail, stunts the competitiveness of exciting new technologies with the potential to transform energy markets.

The following table shows the extent to which consumers can be caught unawares as to whether electricity markets were in frenzy or calm. The inaccuracy of retail prices does not foretell the problem that may be lurking in the current month's wholesale market. Electricity has always represented a fundamentally volatile market and the absence of real-time and hourly prices can make for unpleasant surprises under the market structures that are evolving in today's wholesale markets. That this volatility is unappreciated by consumers constitutes a fundamental flaw in the retail electricity market, a flaw that will prevent the development of a robust competitive electricity market.

City	Period	Peak Wholesale Price (per mwh)	Retail Energy Price (per kwh)	Implicit Discount
Boston	April 2000	$6000.00	$0.0369	99.4%
Los Angeles	August 2000	$350.00	$0.0536	84.7%
New York	August 2000	$1671.08	$0.0857	94.9%
Philadelphia	June 2000	$906.84	$0.0500	94.5%
San Francisco	May 2000	$350.00	$0.0544	85.6%
Washington, D.C.	June 2000	$297.78	$0.0499	83.2%

As indicated by the table, consumers paying energy rates of under four cents per kilowatt hour would no doubt be greatly surprised that included in that rate were hours in which the price reached six ***dollars***. As the Department pursues end-use efficiency and seeds other new energy-related technologies, it should keep in mind that, under current billing protocols reflecting average monthly prices, individual consumers in the marketplace will necessarily compare the efficacy of adopting new practices and technologies against the retail price and not the peak price of electricity. If the only available retail price is the monthly average, the value those new practices or technologies could provide to both the consumer and society at-large will be hidden, and will be lost.

The Problem with Price Averaging

The virtue of price-averaging, namely its simplicity, is also its greatest fault: it is *too* simple. The weighted-average pricing convention prevents the retail consumer from appreciating the product value of electricity, which is not as constant as the convention makes it appear. Price-averaging trains the retail consumer to believe, contrary to everything known about electricity markets, that the choice of flipping a light switch or turning on an air-conditioner at mid-afternoon during the hottest day of summer is identical to that same choice later in the evening. It is not.

The fundamental problem in the retail electricity market is that price-averaging masks the true costs of consumption, thereby precluding any meaningful demand response to rising prices. What is missing from the retail electricity market is a pricing discipline that describes electricity products, e.g., peak power versus choosing to shift demand to lower-cost periods versus a more efficient appliance, to the consumer accurately and precisely. Recently, the New York Independent System Operator adopted a price cap of $1300.00 per megawatt-hour as a proxy for demand responsiveness, specifically justifying its action on the grounds that the absence of a market response to high prices on the consumer side constitutes a serious market flaw.

Consumers need to understand that the value of electricity is not constant, but varies with system demand. Under the current market structure, the product value of electricity is set in the wholesale market by generators and marketers, who price based on their perceptions of shortage and scarcity in both the generation picture and delivery system. If, however, consumers were provided a variety of prices reflecting the differing product values of electricity under various shortage and scarcity conditions, consumers could participate in setting

prices by affecting the supply-demand equilibrium from the consumption end of the equation.

I am convinced that consumers would reject high-priced electricity if they could, and buy low-cost electricity in its place wherever possible. As an example, two percent of California's summer-peak electricity demand is caused by residential clothes drying. Another three percent is caused by residential cooking.[2] If residential consumers knew that electricity consumed at 2:00 PM would cost ten times as much as electricity consumed four hours later, barring unusual circumstances and emergencies most customers would seek to limit their 2:00 PM purchases. Most would prefer to reject the high-priced peak electricity product, shift their usage to a lower-priced period, and pocket the savings. But weighted-average pricing gives them the wrong message.

Price-averaging has the disastrous effect of stalling competition and precluding the best benefits of adopting competitive market structures. Competition is stalled and innovation thwarted because, in the retail electricity market, every competitor and each new product or service must compete against the entire monthly wholesale market. That is, competitors essentially compete against every kilowatt of installed capacity that may be brought to market and every kilowatt-hour that may be consumed since the retail price bundles them all together and presents them at a single price to the consumer. That's a tough business proposition and the ultimate barrier to entry.

Price-averaging effectively sets the demand elasticity of alternatives and choices too low. The best retail competition would occur at the highest priced increments of the market, but the retail price of those increments are represented to consumers at levels substantially below cost. Under today's pricing regime, the consumer comparing the cost of alternative products and services, weighing whether to shift demand to lower cost periods or foregoing consumption altogether, would compare the below-cost price for peak power against the price of alternatives. In many cases, the societally economic choice is uneconomic to the consumer because of the subsidies peak power receives in the retail marketplace. This results in fewer alternatives being selected than should be the case. Demand-side services and appliance efficiency suffer the most from these distortions.

New entrants in the retail end of the electricity business are forced to resort to offering their own weighted-average bundles in order to compete with price-

[2] Keese, William, Chairman, California Energy Commission, "Electricity Supply and Adequacy in the West," Address to the National Conference of State Legislatures Energy Project, July 18, 2000.

averaged power available from the default service provider, usually the incumbent utility, only to receive lukewarm response from consumers who would rather not be bothered with choices offering them savings expressed in pennies per month.

Weighted-average pricing presents electricity as an undifferentiated product. Energy service providers are essentially forced into a competition with a "generic" product, generally being provided by a century-old incumbent with a strong local brand identity. Even worse, customers who stand to benefit most from innovative products and services, that is, those with high-cost load profiles, receive the greatest subsidy under flat-rate pricing and competitors who might serve them are shut out of the market. There may well be a market suited to a flat-rate, "anytime" electricity product, but it does not span the entire spectrum of customers. Hourly pricing can reveal the customers that can be served under a flat price and, more importantly, those who should not be.

Under regulated conditions, consumers were protected from shortage and scarcity pricing by implicit price caps set by regulators. Prices were cost-based and capped at levels meeting local definitions of "prudence." But such regulatory protections are limited in the wholesale markets and consumers, whether they know it or not, are paying prices ranging from under two cents to over five dollars per kilowatt-hour. Exposing the prices at the high end of the spectrum would only serve to reduce them. Few customers would pay the five-dollar prices a kilowatt-hour can draw under extreme market conditions. But price-averaging encourages them to do so. Even worse, those customers who do not purchase peak power, rejecting its high prices, unknowingly subsidize those who do the opposite. And because they are not the customers who participate in competitive electricity procurement or are sought by marketers, the smallest customers tend to be the ones who pay the greatest subsidies.

An important aspect of competitive markets is the range of choices and voluntary decisions the consumer has the ability to select and make. In today's retail electricity markets, consumers have few choices, most of them only marginally distinguishable from one another. Even the largest industrial consumers receive product offerings mimicking generally available wholesale market products. What consumers need, and do not by and large perceive they have, is the ability to refuse to buy and take a pass, the ultimate element of what I would describe as true choice. Since weighted-average pricing obliterates (or at least obscures) the benefits of rejecting certain electricity products, e.g., the peak-period kilowatt-hour with shelf prices of one to five dollars each, consumers don't deny themselves of an otherwise objectionable electricity purchase when they should. For competitive retail markets to emerge, this must change.

From the Sempra perspective, retail electricity markets are in a state of incomplete competition. We see fewer and fewer competitors serving local distribution customers. A recent study indicated that only ten percent of the energy service providers entering the newly opened California market of 1997 remained in business in 1999.[3] Disturbingly, the "default supply service" provided by Sempra, a plain-vanilla service, has become the service of mass choice. This is not what was envisioned when retail competition was adopted. Further structural changes in the retail marketplace will get us closer to the benefits of competition. We believe the next key step in market evolution is the implementation of hourly pricing in the retail sector. This provides for higher-resolution differentiation in electricity products (and, yes, electricity at 3:00 p.m. on a peak summer day is a different product from everything else) and enables competitors to pick and choose which electricity products and services they will either offer or compete against. That these alternative products and services would come available transfers the power of choice from wholesale market participants to the retail consumer, completing the competitive evolution of the electricity market. At this stage, the benefits promised from competition would finally be delivered.

Competitive Benefits

Among the most important benefits of hourly pricing would be a more precise understanding of the price elasticity of electricity demand. As consumers reject power at some prices and consume more at other price levels, we would get a better understanding of optimal energy-system design and resource planning. This is not only important for traditional grid-based electricity products, but it is essential to developing product substitutions and alternative products and services.

Demand Response

There are a number of benefits that would evolve from empowering consumers with true choice. As discussed previously, I believe consumers would reject high-priced electricity in most cases in favor of either foregone consumption or demand shifting. This would reduce peak demand and prices, ease system

[3]Byrne, Warren W., "Green Power in California: First Year Review from a Business Perspective," Foresight Energy, p.14. Of the 250 energy service providers registered to do business in California in 1997, only twenty-seven remained registered in 1999. Only ten were cited as "actively marketing." These companies spent over $250 million to recruit but 200,000 customers out of an eligible meter population of 25,000,000.

constraints, improve operating margins and system reliability, and perhaps reduce the operation of (or even result in the closure of) environmentally or economically high-cost plants that only run at peak.

A demand response to wholesale-market prices would reduce retail prices immediately. Clipping peak demand, even a little bit, would have favorably disproportional impacts on wholesale electricity prices, since most regional markets operate under one-price-clears-all regimes. Eliminating the last increment of demand will ratchet incremental price-setting bids downward, reducing the clearing price paid to the entire supply pool. This can only intensify the competition at the clearing-price end of the wholesale market, potentially eliminating the sometimes out-of-control leapfrogging of daisy-chained contracts that occurs in today's marketplace. Other consumers would search for alternative products and substitutes rather than accept peak-price volatility, creating a demand for innovative products and services, particularly those based on innovations that would avoid consumption of on-peak power.

As part of its recent study on the potential impacts of competition, the Department of Energy compared the possible impact time-of-use pricing could have on retail electricity prices.[4] The study forecasted the impacts of demand elasticity across 108 product segments (six seasons, three types of day, three periods per day, two parts per period) on retail prices using three consumer scenarios. The three scenarios tested flat-rate pricing, time-of-use pricing under moderate demand elasticity, and time-of-use pricing under high demand elasticity. Both scenarios using time-of-use pricing resulted in lower nationwide electricity prices.[5] Under the moderate demand elasticity case, a 1.5 percent change in demand for every ten percent increase in price was forecasted to result in overall retail price reductions of three percent nationwide, with savings at least twice as great occurring in Texas, California-Nevada, New York and the Mid-America Interconnected Network states.[6] These price benefits will be foregone without time-of-use pricing and metering.

[4] "Electricity Prices in a Competitive Environment," Energy Information Administration, U.S. Department of Energy, Office of Integrated Analysis and Forecasting, DOE/EIA-0614, Washington, D.C., August 1997 (updated September 1999). The study did not segment consumers into different groups and it was acknowledged that different consumers would bear different demand elasticities.

[5] *Id.*, at 30. The study broke the country into thirteen regions, generally using the North American Electric Reliability Council regional designations, with some of the regions subdivided for greater study resolution. The study indicated that two of the thirteen regions would suffer higher prices under competitive conditions generally, due to their current resource mix. Low-cost coal generation in the Mid-Continent Area Power Pool and low-cost hydroelectricity in the Pacific Northwest Region of the Western System Coordinating Council starts these regions with embedded costs below marginal generating costs. *Id.*, at pp. 51-52, 57-58.

[6] This is a net price savings taking into account two countervailing effects that would raise prices: general national load growth patterns; and, the increasing cost of mid-peak and off-peak electricity due to increased consumption during these periods caused by load shifting.

Demand responsiveness can be enhanced greatly through the addition of market protocols enabled by hourly metering and real-time pricing. Among the most prominent of these is the emerging market for load-reduction bidding. In simple terms, under certain market conditions customers "sell" load reductions, effected through self-curtailment or the use of proprietary generation, into the system and are paid to reduce consumption during peak periods. A number of these types of programs are sprouting up around the country, emplaced by both utilities and energy service providers who see the flexibility of certain customers to curtail as a valuable asset worth capturing and monetizing.[7] Hourly meters can improve the precision of measuring and compensating the benefits of customer curtailments.

This development fits the long-standing forecasts of a number of energy-industry analysts who have touted the benefits of an electricity market in which "negawatts," i.e., load reductions or demand management practiced on the consumer-side of the meter, would be bought and sold. Implementing hourly pricing structures would pave the way for the further development of load-reduction technologies, trading systems and the appliance improvements that would permit the smallest of customers to participate in negawatt markets.

New Products and Services: Traditional Genus

Unbundling the electricity product into its various hourly components would have the salutary effect of allowing consumer decisions, whether manifested in rejecting power at high

prices or buying alternative products and services, to govern the evolution of the electricity marketplace and the pace of technology, product and service innovation. The current state of competitive electricity markets and unitary pricing conventions will never achieve this result. Rather than have consumers make the key decisions about the products and services they want, legislative intervention and regulatory proceeding after regulatory proceeding defines the nature of competition. Consumers in large part sit on the sidelines, wondering what all the fuss is about. There is a lot of room for new products and services to restructure the electricity market, particularly in peak periods, and we should set

[7] The New York Power Authority has engaged over sixteen megawatts of load reductions in its programs. "NYPA Program Eases Strain on City Electricity Supply," *EnergyCentral*, August 3, 2000. Several vendors of the supporting software systems required, such as Apogee of Atlanta, Georgia, and Silicon Energy of Alameda, California, have signed up utilities as clients. The California Public Utilities Commission has authorized the use of demandside bidding for Pacific Gas & Electric and Southern California Edison. See CPUC Resolutions E-3619 (July 1999), E-3624 (August 1999) and E-3650 (April 2000).

the stage for innovators rather than regulatory economists and lawyers to make the market.

If and when this happens, there are a number of new products and services that would become more competitive if retail prices more accurately reflected the cost of electricity. For example, gas-fired air conditioning, thermal energy storage and distributed generation are in most cases (and even then only at best) marginally competitive under weighted-average electricity pricing. But the competitiveness of these products increases dramatically as grid-delivered electricity is broken into several time-differentiated products using hourly prices to reflect the variable cost of wholesale electricity. The concept of using distributed resources to supplement the delivery capabilities of regional electricity grids has been discussed for many years. Under competitive market conditions, technologies for determining the range of optimal conditions under which distributed resources should be dispatched and for facilitating the automated dispatch of distributed resources when those conditions are met are essential.

The notion that energy service providers could, if given the proper market conditions, create a distinctive product identity for different kinds of electricity is demonstrated by the success of "green power." In most states where customers can select their supplier, competitors offering power generated using renewable fuels and otherwise bearing environmental benefits have created distinctive brands and marketing strategies. Green power has found its market despite the fact that it generally commands a premium price as compared to more "generic" electricity. The American Power Exchange reports green-power premiums in the Midwest markets at between $0.50 to $8.75 per megawatt-hour for the current year, with volumes reaching over 200,000 megawatt-hours in June 2000. California market premiums reached an extraordinary $29.95 per megawatt-hour in November 1999, with monthly averages ranging between two and five dollars.[8]

Even more remarkable is that the market for green power is not limited to fringe environmentalist consumers. Mainstream commercial and industrial customers whose corporate identities include commitments to environmental responsibility and sustainable development are also willing to pay above-market prices for green power. The California operations of Toyota Motors USA are powered exclusively by green power. This represents over 40 million kilowatt-hours

[8]APX Midwest and California Market Exchange Data, www.apx.com/markets; August 2000. Over ninety percent of the 200,000 California electricity consumers that have switched service providers since the opening of retail competition have elected green power. Moore, Michal, Commissioner, California Energy Commission, "Green Power Wins Big in California," *Electricity Daily*.

annually, five percent of this coming from wind generation. Over 1000 facilities of the United States Postal Service have committed to using green power under a three-year agreement with GoGreen.com; the contract covers more than 30 million kilowatt-hours per year. It is not hard to imagine that the green power market could be extended if, rather than paying a premium for renewable resources, consumers were offered *lower bills for shifting their consumption to off-peak hours when fossil plants were not operating*. If green power is a legitimate market niche, other classes of electricity products can surely also exist. In the event hourly pricing is implemented, I would expect to see new product identities to be developed by energy service providers, say an "off-peak" product and perhaps even free nights and weekends where tied to ancillary services.

New Products and Services: Multiplexing the Infrastructure

Among the most exciting opportunities for new products and services in the electricity industry is the potential for achieving the technological convergence between the electricity and telecommunications industries. Powerline-carrier technology has been available commercially for several years but emerging software and hardware solutions indicate the vast potential for unlocking the latent broadband network capabilities of the national electricity grid. In the past, the high-frequency harmonic noise in and the generally uncontrolled and chaotic topology of the power system and local cabling presented daunting obstacles and challenges to using power lines and electrical wiring as a communications medium. But several techniques, including popular spread-spectrum protocols used in consumer electronics bus automation systems for controlling appliances in so-called "smart houses," are coming available that could transform power lines and interior cabling into a new communications architecture. Imagine the extent to which Internet connectivity would be improved if every room of every standing structure carried information in addition to electricity! Such a communications system would present the opportunity to embed termination and translation electronics into every end-use appliance, automating the purchase of electricity at the outlet. This would require upgrades to the metering technology currently in place, turning the meter into a communications relay and information gateway. Smart houses, after all, would not work with dumb meters.

There is also the near-term potential for using powerline-carrier technologies as the fundamental telemetry conveying consumption and pricing data to and from the meter. It is hardly farfetched that new metering technologies could be coupled with Internet-based appliance-control systems to allow retail consumers to accept or reject electricity prices in real-time. Several consortia of preeminent information-technology providers, including Sun Microsystems/Netscape,

Oracle and Excite@Home, are developing technologies that would turn every flat appliance surface into an Internet-connected user interface. Including electricity-consumption controls and displays within that user interface hardly would be a trick and taking advantage of ubiquitous interior, local and regional electricity wiring would speed the adoption of these interfaces as well as enhance their compelling functionality. When these technologies come to market, a consumer could well see the real-time price of electricity on the door of a microwave oven or clothes dryer, and elect then and there whether to flip the switch or wait fifteen minutes for a better electricity price. What an electricity market that would be!

Incentives for Investment in Infrastructure

In addition to the changes that may occur in the dynamic equilibration of supply, demand and market prices, increasing competitive pressure in the electricity industry would spur investment in critical infrastructure. Other deregulated industries experienced dramatic increases in investment as their markets grew more competitive and attention focused on service quality and availability.

In the domestic telecommunications industry, immediately following their divestiture from AT&T, the regional operating companies tripled their fiber-optic cable during 1985 to 1987, a trend followed by other competitors. This decreased the regional companies' cost-per-meter of line to under twelve cents by 1995, well under the 1980 figure of $2.50 per meter. Similarly, investments in digital switching were accelerated as a result of competition, once again resulting in lower costs to consumers and enhanced service capability.

Passenger air service saw a similar pattern of investment. Nationwide airport expansions and upgrades were triggered by the growing number of carriers and flights. The national air-traffic control system has seen over $3.8 billion of investment to accommodate the needs of today's market.

Comparable investment in the electricity industry could be made in the transmission grid, either to improve local reliability or enhance capacity. At present, investment in transmission upgrades and expansion projects has fallen sharply in the last few years as uncertainty in the market clouds both responsibility and returns.[9] In addition to bulk upgrades, NERC has been citing

[9]The North American Electric Reliability Council forecasts that only 6,978 miles of new transmission lines will be built during the next ten years, representing a little more than a three-percent enhancement to current facilities, well behind the pace of demand growth and transactional requirements. See "Reliability Assessment: 1999-2000, The Reliability of Bulk Electric Systems in North America," May 2000, at p. 7.

with increased frequency the need to bolster local voltage support on transmission and distribution systems.[10] A number of emerging technologies for improving transmission-system operations and reliability are coming into the market. Flexible AC transmission system technologies offer the potential for highly precise control and measurement of power flows. Corona cameras that reveal transmission-line electromagnetic-field phenomena facilitate the detection of faulty lines and substation components. Video sag meters are replacing theory-based algorithms for determining line ratings and limits. Increasing the level of competition in the industry and clarifying competitors' roles, rights and rewards could only help to reverse current investment trends, speeding the addition of new capacity and installation of these exciting new technologies.

Implementing Hourly Pricing for Retail Electricity

Pricing electricity and billing retail consumers on an hourly basis would require more frequent meter reading than is presently the case. Fortunately, a number of technologies exist to facilitate hourly meter reading. Radio-based polling systems can read meters and record consumption levels at two-minute intervals, far more precision than is necessary for the purposes of implementing hourly retail pricing. Interconnection with existing telecommunications systems offers another medium for transmitting meter data. Both usage and billing data can be combined into real-time and high-resolution views accessible by customers via the Internet.

A price-based billing convention with a few understandable tiers would also simplify the type of commodity-price-reporting local newspapers, web sites and other information providers might offer to retail consumers. In a small box placed next to the weather, newspapers could report the hours of the day falling into the typical billing tiers (two to three cents, three to four cents, etc.). Consumers could adjust their electricity consumption accordingly. To reflect extreme prices or prices otherwise above the last numerically represented cents-per-kilowatt-hour tier, information sources and the monthly billings could use the notational convention my favorite restaurant uses for its (typically expensive) catch-of-the-day specials, a simple *A.C.* This notation could become a well-understood signal that electricity prices are volatile and could be extreme. My expectation is that *Ante Cibrum* (i.e., before eating) warnings and pricing would be much more effective at curbing electricity demand on extreme-peak days than

[10] Ibid, at p. 34.

broadcasting last-minute pleas to consumers to conserve energy voluntarily as is done today.

Sooner is Better than Later

The incomplete competition found in today's retail-electricity market is undermining the long-term prospects for a robust and dynamic marketplace. Energy service providers in jurisdiction after jurisdiction are exiting the market or limping through quarter after quarter of high customer-acquisition costs and thin or nonexistent margins. If they exit, they will leave a trail of customers who will be reluctant to switch again. This adds to the message being played in the current market that the best choice is to stand pat. Allowing this situation to continue will increase the barriers to entry for future competitors and ensure the failure of worthy energy service providers and their innovative products and services.

Hourly pricing in the retail electricity market is at its heart the essential information consumers need to exercise choice and make real decisions about their energy habits and consumption. Weighted-average pricing hasn't taught consumers much about electricity products and choices and, if anything, it has taught them some woeful fictions. With pricing information reflecting the highly variable product value of electricity, consumers would be positioned to demand more benefits, products and services from their service providers and thus armed to participate in the shaping of the electricity market and the competitive landscape.

In a retail market offering unbundled hourly prices, consumers would have true choice. They could reject high-priced electricity in favor of lower prices or reduce their consumption altogether. They would be empowered to make real decisions and exert a huge influence on the prices paid in upstream wholesale markets, giving them some measure of bargaining power with wholesale producers and marketers. Any stubbornness on the part of the wholesale market to meet consumer demands would provide incentives for new entrants with alternative products and services to enter the game. Those alternatives have the potential to provide ancillary but directly related results such as improved system reliability and power quality, environmental benefits or energy efficiency, creating the wholistic market for energy products that regulators have attempted to forge for decades.

Markets work. But the incomplete competition of today's retail electricity is missing key elements that might otherwise encourage consumer participation, true choice and market evolution. Hourly pricing of electricity would be a huge

first step to achieving a real market. Sempra firmly believes that this next step should be adopted sooner rather than later so as to speed the proliferation of competitive benefits to the consumer.

Raising the Speed Limit: U.S. Economic Growth in the Information Age

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The continued strength and vitality of the U.S. economy continues to astonish economic forecasters.[2] A consensus is now emerging that something fundamental has changed with "new economy" proponents pointing to information technology as the causal factor behind the strong performance of the U.S. economy. In this view, technology is profoundly altering the nature of business, leading to permanently higher productivity growth throughout the economy. Skeptics argue that the recent success reflects a series of favorable, but temporary, shocks. This argument is buttressed by the view that the U.S. economy behaves rather differently than envisioned by new economy advocates.[3]

While productivity growth, capital accumulation, and the impact of technology were once reserved for academic debates, the recent success of the U.S. economy has moved these topics into popular discussion. The purpose of this paper is to employ well-tested and familiar methods to analyze important new information made available by the recent benchmark revision of the U.S. National Income and Product Accounts (NIPA). We document the case for raising the speed limit—for upward revision of intermediate-term projections of future growth to reflect the latest data and trends.

The late 1990s have been exceptional in comparison with the growth experience of the U.S. economy over the past quarter century. While growth rates in the

[1]Note that the contents present the views of their authors, not necessarily those of the Department of Energy, RAND, or any other organization with which the authors may be affiliated.

[2]Labor productivity growth for the business sector averaged 2.7% for 1995-99, the four fastest annual growth rates in the 1990s, except for a temporary jump of 4.3% in 1992 as the economy exited recession (BLS (2000)).

[3]Stiroh (1999) critiques alternative new economy views, Triplett (1999) examines data issues in the new economy debate, and Gordon (1999b) provides an often-cited rebuttal of the new economy thesis.

1990s have not yet returned to those of the golden age of the U.S. economy in the 1960s, the data nonetheless clearly reveal a remarkable transformation of economic activity. Rapid declines in the prices of computers and semiconductors are well known and carefully documented, and evidence is accumulating that similar declines are taking place in the prices of software and communications equipment. Unfortunately, the empirical record is seriously incomplete, so much remains to be done before definitive quantitative assessments can be made about the complete role of these high-tech assets.

Despite the limitations of the available data, the mechanisms underlying the structural transformation of the U.S. economy are readily apparent. As an illustration, consider the increasing role that computer hardware plays as a source of economic growth.[4] For the period 1959 to 1973, computer inputs contributed less than one-tenth of one percent to U.S. economic growth. Since 1973, however, the price of computers has fallen at historically unprecedented rates and firms and households have followed a basic principle of economics—they have substituted towards relatively cheaper inputs. Since 1995 the price decline for computers has accelerated, reaching nearly 28% per year from 1995 to 1998. In response, investment in computers has exploded and the growth contribution of computers increased more than five-fold to 0.46 percentage points per year in the late 1990s.[5] Software and communications equipment, two other information technology assets, contributed an additional 0.29 percentage points per year for 1995-98. Preliminary estimates through 1999 reveal further increases in these contributions for all three high-tech assets.

Next, consider the acceleration of average labor productivity (ALP) growth in the 1990s. After a 20-year slowdown dating from the early 1970s, ALP grew 2.4% per year for 1995-98, more than a percentage point faster than during 1990-95.[6] A detailed decomposition shows that capital deepening, the direct consequence of price-induced substitution and rapid investment, added 0.49 percentage points to ALP growth. Faster total factor productivity (TFP) growth contributed an additional 0.63 percentage points, largely reflecting technical change in the

[4]Our work on computers builds on the path-breaking research of Oliner and Sichel (1994, 2000) and Sichel (1997, 1999), and our own earlier results, reported in Jorgenson and Stiroh (1995, 1999, 2000) and Stiroh (1998a). Other valuable work on computers includes Haimowitz (1998), Kiley (1999), and Whelan (1999). Gordon (1999a) provides valuable historical perspective on the sources of U.S. economic growth and Brynjolfsson and Yang (1996) review the micro evidence on computers and productivity.

[5]See Baily and Gordon (1988), Stiroh (1998a), Jorgenson and Stiroh (1999) and Department of Commerce (1999) for earlier discussions of relative price changes and input substitution in the high-tech areas.

[6]BLS (2000) estimates for the business sector show a similar increase from 1.6% for 1990-95 to 2.6% for 1995-98. See CEA (2000, pg. 35) for a comparison of productivity growth at various points in the economic expansions of the 1960s, 1980s, and 1990s.

production of computers and the resulting acceleration in the price decline of computers. Slowing labor quality growth retarded ALP growth by 0.12 percentage points, relative to the early 1990s, a result of exhaustion of the pool of available workers.

Focusing more specifically on TFP growth, this was an anemic 0.34% per year for 1973-95, but accelerated to 0.99% for 1995-98. After more than twenty years of sluggish TFP growth, four of the last five years have seen growth rates near 1%. It could be argued this represents a new paradigm. According to this view, the diffusion of information technology improves business practices, generates spillovers, and raises productivity throughout the economy. If this trend is sustainable, it could revive the optimistic expectations of the 1960s and overcome the pessimism of The Age of Diminished Expectations, the title of Krugman's (1990) influential book.

A closer look at the data, however, shows that gains in TFP growth can be traced in substantial part to information technology industries, which produce computers, semiconductors, and other high-tech gear. The evidence is equally clear that computer-using industries like finance, insurance, and real estate (FIRE) and services have continued to lag in productivity growth. Reconciliation of massive high-tech investment and relatively slow productivity growth in service industries remains an important task for proponents of the new economy position.[7]

What does this imply for the future? The sustainability of growth in labor productivity is the key issue for future growth projections. For some purposes, the distinctions among capital accumulation and growth in labor quality and TFP may not matter, so long as ALP growth can be expected to continue. It is sustainable labor productivity gains, after all, that ultimately drive long-run growth and raise living standards.

In this respect, the recent experience provides grounds for caution, since much depends on productivity gains in high-tech industries. Ongoing technological gains in these industries have been a direct source of improvement in TFP growth, as well as an indirect source of more rapid capital deepening. Sustainability of growth, therefore, hinges critically on the pace of technological progress in these industries. As measured by relative price changes, progress has accelerated recently, as computer prices fell 28% per year for 1995-98 compared to 15% in 1990-95. There is no guarantee, of course, of continued productivity

[7] See Gullickson and Harper (1999), Jorgenson and Stiroh (2000), and Section IV, below, for industry-level analysis.

gains and price declines of this magnitude. Nonetheless, as long as high-tech industries maintain the ability to innovate and improve their productivity at rates comparable to their long-term averages, relative prices will fall and the virtuous circle of an investment-led expansion will continue.[8]

Finally, we argue that rewards from new technology accrue to the direct participants; first, to the innovating industries producing high-tech assets and, second, to the industries that restructure to implement the latest information technology. There is no evidence of spillovers from production of information technology to the industries that use this technology. Indeed, many of the industries that use information technology most intensively, like FIRE and services, show high rates of substitution of information technology for other inputs and relatively low rates of productivity growth. In part, this may reflect problems in measuring the output from these industries, but the empirical record provides little support for the "new economy" picture of spillovers cascading from information technology producers onto users of this technology.[9]

The paper is organized as follows. Section II describes our methodology for quantifying the sources of U.S. economic growth. We present results for the period 1959-1998, and focus on the "new economy" era of the late 1990s. Section III explores the implications of the recent experience for future growth, comparing our results to recent estimates produced by the Congressional Budget Office, the Council of Economic Advisors, and the Office of Management and Budget. Section IV moves beyond the aggregate data and quantifies the productivity growth at the industry level. Using methodology introduced by Domar (1961), we consider the impact of information technology on aggregate productivity. Section V concludes.

The Recent U.S. Growth Experience

The U.S. economy has undergone a remarkable transformation in recent years with growth in output, labor productivity, and total factor productivity all accelerating since the mid-1990s. This growth resurgence has led to a widening debate about sources of economic growth and changes in the structure of the economy. "New economy" proponents trace the changes to developments in

[8]There is no consensus, however, that technical progress in computer and semiconductor production is slowing. According to Fisher (2000), chip processing speed continues to increase rapidly. Moreover, the product cycle is accelerating as new processors are brought to market more quickly.

[9]See Dean (1999) and Gullickson and Harper (1999) for the BLS perspective on measurement error; Triplett and Bosworth (2000) provide an overview of measuring output in the service industries.

information technology, especially the rapid commercialization of the Internet, that are fundamentally changing economic activity. "Old economy" advocates focus on lackluster performance during the first half of the 1990s, the increase in labor force participation and rapid decline in unemployment since 1993, and the recent investment boom.

Our objective is to quantify the sources of the recent surge in U.S. economic growth, using new information made available by the benchmark revision of the U.S. National Income and Product Accounts (NIPA) released in October 1999, BEA (1999). We then consider the implications of our results for intermediate-term projections of U.S. economic growth. We give special attention to the rapid escalation in growth rates in the official projections, such as those by the Congressional Budget Office (CBO) and the Council of Economic Advisers (CEA). The CBO projections are particularly suitable for our purposes, since they are widely disseminated, well documented, and represent "best practice." We do not focus on the issue of inflation and do not comment on potential implications for monetary policy.

Sources of Economic Growth

Our methodology is based on the production possibility frontier introduced by Jorgenson (1966) and employed by Jorgenson and Griliches (1967). This captures substitutions among outputs of investment and consumption goods, as well inputs of capital and labor. We identify information technology (IT) with investments in computers, software, and communications equipment, as well as consumption of computer and software as outputs. The service flows from these assets are also inputs. The aggregate production function employed by Solow (1957, 1960) and, more recently by Greenwood, Hercowitz, and Krusell (1997), is an alternative to our model. In this approach a single output is expressed as a function of capital and labor inputs. This implicitly assumes, however, that investments in information technology are perfect substitutes for other outputs, so that relative prices do not change.

Our methodology is essential in order to capture two important facts about which there is general agreement. The first is that prices of computers have declined drastically relative to the prices of other investment goods. The second is that this rate of decline has recently accelerated. In addition, estimates of investment in software, now available in the NIPA, are comparable to investment in hardware. The new data show that the price of software has fallen relative to the prices of other investment goods, but more slowly than price of hardware. We examine the estimates of software investment in some detail in order to

assess the role of software in recent economic growth. Finally, we consider investment in communications equipment, which shares many of the technological features of computer hardware.

Production Possibility Frontier. Aggregate output Yt consists of investment goods It and consumption goods Ct. These outputs are produced from aggregate input Xt, consisting of capital services Kt and labor services Lt. We represent productivity as a "Hicks-neutral" augmentation At of aggregate input:[10]

$$(1) \qquad Y(I_t, C_t) = A_t \cdot X(K_t, L_t)\,.$$

The outputs of investment and consumption goods and the inputs of capital and labor services are themselves aggregates, each with many sub-components.

Under the assumptions of competitive product and factor markets, and constant returns to scale, growth accounting gives the share-weighted growth of outputs as the sum of the share-weighted growth of inputs and growth in total factor productivity (TFP):

$$(2) \qquad \overline{w}_{I,t}\Delta \ln I_t + \overline{w}_{C,t}\Delta \ln C_t = \overline{v}_{K,t}\Delta \ln K_t + \overline{v}_{L,t}\Delta \ln L_t + \Delta \ln A_t\,,$$

where $\overline{w}_{I,t}$ is investment's average share of nominal output, $\overline{w}_{C,t}$ is consumption's average share of nominal output, $\overline{v}_{K,t}$ is capital's average share of nominal income, $\overline{v}_{K,t}$ is labor's average share of nominal income, $\overline{w}_{I,t} + \overline{w}_{C,t} = \overline{v}_{K,t} + \overline{v}_{L,t} = 1$, and D refers to a first difference. Note that we reserve the term total factor productivity for the augmentation factor in Equation (1).

Equation (2) enables us to identify the contributions of outputs as well as inputs to economic growth. For example, we can quantify the contributions of different investments, such as computers, software, and communications equipment, to the growth of output by decomposing the growth of investment among its sub-components. Similarly, we can quantify the contributions of different types of consumption, such as services from computers and software, by decomposing the growth of consumption. As shown in Jorgenson and Stiroh (1999), both computer investment and consumption of IT have made important contributions to U.S. economic growth in the 1990s. We also consider the output contributions of software and communications equipment as distinct high-tech assets. Similarly, we decompose the contribution of capital input to isolate the impact of computers, software, and communications equipment on input growth.

[10] It would be a straightforward change to make technology labor-augmenting or "Harrod-neutral," so that the production possibility frontier could be written: $Y(I, C) = X(K,AL)$. Also, there is no need to assume that inputs and outputs are separable, but this simplifies our notation.

Rearranging Equation (2) enables us to present our results in terms of growth in average labor productivity (ALP), defined as $y_t = Y_t / H_t$, where Yt is output, defined as an aggregate of consumption and investment goods, and $k_t = K_t / H_t$ is the ratio of capital services to hours worked Ht:

$$(3) \qquad \Delta \ln y_t = \overline{v}_{K,t} \Delta \ln k_t + \overline{v}_{L,t} (\Delta \ln L_t - \Delta \ln H_t) + \Delta \ln A_t \, .$$

This gives the familiar allocation of ALP growth among three factors. The first is capital deepening, the growth in capital services per hour. Capital deepening makes workers more productive by providing more capital for each hour of work and raises the growth of ALP in proportion to the share of capital. The second term is the improvement in labor quality, defined as the difference between growth rates of labor input and hours worked. Reflecting the rising proportion of hours supplied by workers with higher marginal products, labor quality improvement raises ALP growth in proportion to labor's share. The third factor is TFP growth, which increases ALP growth on a point-for-point basis.

Computers, Software, and Communications Equipment. We now consider the impact of investment in computers, software, and communications equipment on economic growth. For this purpose we must carefully distinguish the use of information technology and the production of information technology.[11] For example, computers themselves are an output from one industry (the computer-producing industry, Commercial and Industrial Machinery), and computing services are inputs into other industries (computer-using industries like Trade, FIRE, and Services).

Massive increases in computing power, like those experienced by the U.S. economy, therefore reflect two effects on growth. First, as the production of computers improves and becomes more efficient, more computing power is being produced from the same inputs. This raises overall productivity in the computer-producing industry and contributes to TFP growth for the economy as a whole. Labor productivity also grows at both the industry and aggregate levels.[12]

Second, the rapid accumulation of computers leads to input growth of computing power in computer-using industries. Since labor is working with

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[11]Baily and Gordon (1988), Griliches (1992), Stiroh (1998a), Jorgenson and Stiroh (1999), Whelan (1999), and Oliner and Sichel (2000) discuss the impact of investment in computers from these two perspectives.

[12]Triplett (1996) points out that much of decline of computer prices reflects falling semiconductor prices. If all inputs are correctly measured for quality change, therefore, much of the TFP gains in computer production are rightly pushed back to TFP gains in semiconductor production since semiconductors are a major intermediate input in the production of computers. See Flamm (1993) for early estimates on semiconductor prices. We address this further in Section IV.

more and better computer equipment, this investment increases labor productivity. If the contributions to output are captured by the effect of capital deepening, aggregate TFP growth is unaffected. As Baily and Gordon (1988) remark, "there is no shift in the user firm's production function (pg. 378)," and thus no gain in TFP. Increasing deployment of computers increases TFP only if there are spillovers from the production of computers to production in the computer-using industries, or if there are measurement problems associated with the new inputs.

We conclude that rapid growth in computing power affects aggregate output through both TFP growth and capital deepening. Progress in the technology of computer production contributes to growth in TFP and ALP at the aggregate level. The accumulation of computing power in computer-using industries reflects the substitution of computers for other inputs and leads to growth in ALP. In the absence of spillovers this growth does not contribute to growth in TFP.

The remainder of this section provides empirical estimates of the variables in Equations (1) through (3). We then employ Equations (2) and (3) to quantify the sources of growth of output and ALP for 1959-1998 and various sub-periods.

Output

Our output data are based on the most recent benchmark revision of NIPA.[13] Real output Yt is measured in chained 1996 dollars, and PY,t is the corresponding implicit deflator. Our output concept is similar, but not identical, to one used in the Bureau of Labor Statistics (BLS) productivity program. Like BLS, we exclude the government sector, but unlike BLS we include imputations for the service flow from consumers' durables and owner-occupied housing. These imputations are necessary to preserve comparability between durables and housing and also enable us to capture the important impact of information technology on households.

Our estimate of current dollar, private output in 1998 is $8,013B, including imputations of $740B that primarily reflect services of consumers' durables.[14] Real output growth was 3.63% for the full period, compared to 3.36% for the official GDP series. This difference reflects both our imputations and our

[13]See Appendix A for details on our source data and methodology for output estimates.

[14]Current dollar NIPA GDP in 1998 was $8,759.9B. Our estimate of $8,013B differs due to total imputations ($740B), exclusion of general government and government enterprise sectors ($972B and $128B, respectively, and exclusion of certain retail taxes ($376B).

exclusion of the government sectors in the NIPA data. Appendix Table A-1 presents the current dollar value and corresponding price index of total output and the IT assets—investment in computers Ic, investment in software Is, investment in communications equipment Im, consumption of computers and software Cc, and the imputed service flow from consumers' computers and software, Dc.

The most striking feature of these data is the enormous price decline for computer investment, 18% per year from 1960 to 1995 (Chart 1). Since 1995 this decline has accelerated to 27.6% per year. By contrast the relative price of software has been flat for much of the period and only began to fall in the late 1980s. The price of communications equipment behaves similarly to the software price, while consumption of computers and software shows declines similar to computer investment. The top panel of Table 1 summarizes the growth rates of prices and quantities for major output categories for 1990-95 and for 1995-98.

In terms of current dollar output, investment in software is the largest IT asset, followed by investment in computers and communications equipment (Chart 2). While business investments in computers, software, and communications equipment are by far the largest categories, households have spent more than $20B per year on computers and software since 1995, generating a service flow of comparable magnitude.

Capital Stock and Capital Services

This section describes our capital estimates for the U.S. economy from 1959 to 1998.[15] We begin with investment data from the Bureau of Economic Analysis, estimate capital stocks using the perpetual inventory method, and aggregate capital stocks using rental prices as weights. This approach, originated by Jorgenson and Griliches (1967), is based on the identification of rental prices with marginal products of different types of capital. Our estimates of these prices incorporate differences in asset prices, service lives and depreciation rates, and the tax treatment of capital incomes.[16]

We refer to the difference between growth in capital services and capital stock as the growth in capital quality $q_{K,t}$; this represents substitution towards assets

[15] See Appendix B for details on theory, source data, and methodology for capital estimates.

[16] Jorgenson (1996) provides a recent discussion of our model of capital as a factor of production. BLS (1983) describes the version of this model employed in the official productivity statistics. Hulten (2000) provides a review of the specific features of this methodology for measuring capital input and the link to economic theory.

with higher marginal products.[17] For example, the shift toward IT increases the quality of capital, since computers, software, and communications equipment have relatively high marginal products. Capital stock estimates, like those originally employed by Solow (1957), fail to account for this increase in quality.

We employ a broad definition of capital, including tangible assets such as equipment and structures, as well as consumers' durables, land, and inventories. We estimate a service flow from the installed stock of consumers' durables, which enters our measures of both output and input. It is essential to include this service flow, since a steadily rising proportion is associated with investments in IT by the household sector. In order to capture the impact of information technology on U.S. economic growth, investments by business and household sectors as well as the services of the resulting capital stocks must be included.

Our estimate of capital stock is $26T in 1997, substantially larger than the $17.3T in fixed private capital estimated by BEA (1998b). This difference reflects our inclusion of consumer's durables, inventories, and land. Our estimates of capital stock for comparable categories of assets are quite similar to those of BEA. Our estimate of fixed private capital in 1997, for example, is $16.8T, almost the same as that of BEA. Similarly, our estimate of the stock of consumers' durables is $2.9T, while BEA's estimate is $2.5T. The remaining discrepancies reflect our inclusion of land and inventories. Appendix Table B-1 list the component assets and 1998 investment and stock values; Table B-2 presents the value of capital stock from 1959 to 1998, as well as price indices for total capital and IT assets.

The stocks of IT business assets (computers, software, and communications investment equipment), as well as consumers' purchases of computers and software, have grown dramatically in recent years, but remain relatively small. In 1998, combined IT assets accounted for only 3.4% of tangible capital, and 4.6% of reproducible, private assets.

We now move to estimates of capital services flows, where capital stocks of individual assets are aggregated using rental prices as weights. Appendix Table B-3 presents the current dollar service flows and corresponding price indexes for 1959-98, and the second panel of Table 1 summarizes the growth rates for prices and quantities of inputs for 1990-95 and 1995-98.

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[17] More precisely, growth in capital quality is defined as the difference between the growth in capital services and the growth in the average of the current and lagged stock. Appendix B provides details. We use a geometric depreciation rate for all reproducible assets, so that our estimates are not identical to the wealth estimates published by BEA (1998b).

There is a clear acceleration of growth of aggregate capital services from 2.8% per year for 1990-95 to 4.8% for 1995-98. This is largely due to rapid growth in services from IT equipment and software, and reverses the trend toward slower capital growth through 1995. While information technology assets are only 11.2% of the total, the service shares of these assets are much greater than the corresponding asset shares. In 1998 capital services are only 12.4% of capital stocks for tangible assets as a whole, but services are 40.0% of stocks for information technology. This reflects the rapid price declines and high depreciation rates that enter into the rental prices for information technology.

Chart 3 highlights the rapid increase in the importance of IT assets, reflecting the accelerating pace of relative price declines. In the 1990s, the service price for computer hardware fell 14.2% per year, compared to an increase of 2.2% for non-information technology capital. As a direct consequence of this relative price change, computer services grew 24.1%, compared to only 3.6% for the services of non-IT capital in the 1990s. The current dollar share of services from computer hardware reached nearly 3.5% of all capital services in 1998.[18]

The rapid accumulation of software, however, appears to have different origins. The price of software investment has declined much more slowly, -1.7% per year for software versus -19.5% for computer hardware for 1990 to 1998. These differences in investment prices lead to a much slower decline in service prices for software and computers, -1.6% versus -14.2%. Nonetheless, firms have been accumulating software quite rapidly, with real capital services growing 13.3% per year in the 1990s. While lower than the 24.1% growth in computers, software growth is much more rapid than growth in other forms of tangible capital. Complementarity between software and computers is one possible explanation. Firms respond to the decline in relative computer prices by accumulating computers and investing in complementary inputs like software to put the computers into operation.[19]

A competing explanation is that the official price indexes used to deflate software investment omit a large part of true quality improvements. This would lead to a substantial overstatement of price inflation and a corresponding understatement of real investment, capital services, and economic growth. According to Moulton, Parker, and Seskin (1999) and Parker and Grimm (2000), only prices for

[18]Tevlin and Whelan (1999) provide empirical support for this explanation, reporting that computer investment is particularly sensitive to the cost of capital, so that the rapid drop in service prices can be expected to lead to large investment response.

[19]An econometric model of the responsiveness of different types of capital services to own- and cross-price effects could be used to test for complementarity, but this is beyond the scope of the paper.

prepackaged software are calculated from constant-quality price deflators based on hedonic methods. Prices for business own-account software are based on input-cost indexes, which implicitly assume no change in the productivity of computer programmers. Custom software prices are a weighted average of prepackaged software and own-account software, with an arbitrary 75% weight for business own-account software prices. Thus, the price deflators for nearly two-thirds of software investment are estimated under the maintained assumption of no gain in productivity.[20] If the quality of own-account and custom software is improving at a pace even remotely close to packaged software, this implies a large understatement in investment in software.

Although the price decline for communications equipment during the 1990s is comparable to that of software, as officially measured in the NIPA, investment has grown at a rate that is more in line with prices. However, there are also possible measurement biases in the pricing of communications equipment. The technology of switching equipment, for example, is similar to that of computers; investment in this category is deflated by a constant-quality price index developed by BEA. Conventional price deflators are employed for transmission gear, such as fiber-optic cables, which also appear to be declining rapidly in price. This could lead to an underestimate of the rate of growth in communications equipment investment, capital stock, and capital services, as well as an overestimate of the rate of inflation.[21] We return to this issue at the end of Section II.

Measuring Labor Services

This section describes our estimates of labor input for the U.S. economy from 1959 to 1998. We begin with individual data from the Census of Population for 1970, 1980, and 1990, as well as the annual Current Population Surveys. We estimate constant quality indexes for labor input and its price to account for heterogeneity of the workforce across sex, employment class, age, and education levels. This follows the approach of Jorgenson, Gollop and Fraumeni (1987), whose estimates have been revised and updated by Ho and Jorgenson (1999).[22]

[20] According to Parker and Grimm (2000), total software investment of $123.4B includes $35.7B in prepackaged software, $42.3B in custom software, and $45.4B in own-account software in 1998. Applying the weighting conventions employed by BEA, this implies $46.3B=$35.7B+0.25*$42.3B, or 38% of the total software investment, is deflated with explicit quality adjustments.

[21] Grimm (1997) presents hedonic estimates for digital telephone switches and reports average price declines of more than 10% per year from 1985 to 1996.

[22] Appendix C provides details on the source data and methodology.

The distinction between labor input and labor hours is analogous to the distinction between capital services and capital stock. Growth in labor input reflects the increase in labor hours, as well as changes in the composition of hours worked as firms substitute among heterogeneous types of labor. We define the growth in labor quality as the difference between the growth in labor input and hours worked. Labor quality reflects the substitution of workers with high marginal products for those with low marginal products, while the growth in hours employed by Solow (1957) and others does not capture this substitution. Appendix Table C-1 presents our estimates of labor input, hours worked, and labor quality.

Our estimates show the value of labor expenditures to be $4,546B in 1998, roughly 57% of the value of output. This value share accurately reflects the NIPA measure of output and our imputations for capital services. If we exclude these imputations, labor's share rises to 62%, in line with conventional estimates. As shown in Table 1, the growth of the index of labor input Lt appropriate for our model of production in Equation (1) accelerated to 2.8% for 1995-98, from 2.0% for 1990-95. This is primarily due to the growth of hours worked, which rose from 1.4% for 1990-95 to 2.4% for 1995-98, as labor force participation increased and unemployment rates plummeted.[23]

The growth of labor quality decelerated in the late 1990s, from 0.65% for 1990-95 to 0.43% for 1995-98. This slowdown captures well-known underlying demographic trends in the composition of the work force, as well as exhaustion of the pool of available workers as unemployment rates have steadily declined. Projections of future economic growth that omit labor quality, like those of CBO, implicitly incorporate changes in labor quality into measured TFP growth. This reduces the reliability of projections of future economic growth. Fortunately, this is easily remedied by extrapolating demographic changes in the work force in order to reflect foreseeable changes in composition by characteristics of workers such as age, sex, and educational attainment.

Quantifying the Sources of Growth

Table 2 presents results of our growth accounting decomposition based on Equation (2) for the period 1959 to 1998 and various sub-periods, as well as preliminary estimates through 1999. As in Jorgenson and Stiroh (1999), we

[23] By comparison, BLS (2000) reports growth in business hours of 1.2% for 1990-95 and 2.3% for 1995-98. The slight discrepancies reflect our methods for estimating hours worked by the self-employed, as well as minor differences in the scope of our output measure

decompose economic growth by both output and input categories in order to quantify the contribution of information technology (IT) to investment and consumption outputs, as well as capital and consumers' durable inputs. We extend our previous treatment of the outputs and inputs of computers by identifying software and communications equipment as distinct IT assets.

To quantify the sources of IT-related growth more explicitly, we employ the extended production possibility frontier:

$$(4) \qquad Y(Y_n, C_c, I_c, I_s, I_m, D_c) = A \cdot X(K_n, K_c, K_s, K_m, D_n, D_c, L)$$

where outputs include computer and software consumption Cc, computer investment Ic, software investment Is, telecommunications investment Im, the services of consumers' computers and software Dc, and other outputs Yn, Inputs include the capital services of computers Kc, software Ks, telecommunications equipment Km, and other capital assets Kn, services of consumers' computers and software Dc and other durables Dn, and labor input L.[24] As in Equation (1), total factor productivity is denoted by A and represents the ability to produce more output from the same inputs. Time subscripts have been dropped for convenience.

The corresponding extended growth accounting equation is:

(5)

$$\begin{aligned} &\bar{w}_{Yn}\Delta \ln Y_n + \bar{w}_{Cc}\Delta \ln C_c + \bar{w}_{Ic}\Delta \ln I_c + \bar{w}_{Is}\Delta \ln I_s + \bar{w}_{Im}\Delta \ln I_m + \bar{w}_{Dc}\Delta \ln D_c = \\ &\quad \bar{v}_{Kn}\Delta \ln K_n + \bar{v}_{Kc}\Delta \ln K_c + \bar{v}_{Ks}\Delta \ln K_s + \bar{v}_{Km}\Delta \ln K_m + \bar{v}_{Dn}\Delta \ln D_n + \bar{v}_{Dc}\Delta \ln D_c + \bar{v}_L\Delta \ln L + \Delta \ln A \end{aligned}$$

where $\bar{w}$ and $\bar{v}$ denote average shares in nominal income for the subscripted variable $\bar{w}_{Yn} + \bar{w}_{Cc} + \bar{w}_{Ic} + \bar{w}_{Is} + \bar{w}_{Im} + \bar{w}_{Dc} = \bar{v}_{Kn} + \bar{v}_{Kc} + \bar{v}_{Ks} + \bar{v}_{Km} + \bar{v}_{Dn} + \bar{v}_{Dc} + \bar{v}_L = 1$, and we refer to a share-weighted growth rate as the contribution of an input or output.

Output Growth. We first consider the sources of output growth for the entire period 1959 to 1998. Capital services make the largest growth contribution of 1.8 percentage point (1.3 percentage points from business capital and 0.5 from consumers' durable assets), labor services contribute 1.2 percentage points, and TFP growth is responsible for only 0.6 percentage points. Input growth is the source of nearly 80 percent of U.S. growth over the past 40 years, while TFP has

[24]Note we have broken broadly defined capital into tangible capital services, *K*, and consumers' durable services, *D*.

accounted for approximately one-fifth. Chart 4 highlights this result by showing the relatively small growth contribution of the TFP residual in each sub-period.

More than three-quarters of the contribution of broadly defined capital reflects the accumulation of capital stock, while increased labor hours account for slightly less than three-quarters of labor's contribution. The quality of both capital and labor have made important contributions, 0.45 percentage points and 0.32 percentage points per year, respectively. Accounting for substitution among heterogeneous capital and labor inputs is therefore an important part of quantifying the sources of economic growth.

A look at the U.S. economy before and after 1973 reveals some familiar features of the historical record. After strong output and TFP growth in the 1960s and early 1970s, the U.S. economy slowed markedly through 1990, with output growth falling from 4.3% to 3.1% and TFP growth falling almost two-thirds of a percentage point from 1.0% to 0.3%. Growth in capital inputs also slowed, falling from 5.0% for 1959-73 to 3.8% for 1973-90, which contributed to sluggish ALP growth, 2.9% for 1959-73 to 1.4% for 1973-90.

We now focus on the period 1995-98 and highlight recent changes.[25] Relative to the early 1990s, output growth has increased by nearly two percentage points. The contribution of capital jumped by 1.0 percentage point, the contribution of labor rose by 0.4 percentage points, and TFP growth accelerated by 0.6 percentage point. ALP growth rose 1.0 percentage point. The rising contributions of capital and labor encompass several well-known trends in the late 1990s. Growth in hours worked accelerated as labor markets tightened, unemployment fell to a 30-year low, and labor force participation rates increased.[26] The contribution of capital reflects the investment boom of the late 1990s as businesses poured resources into plant and equipment, especially computers, software, and communications equipment.

The acceleration in TFP growth is perhaps the most remarkable feature of the data. After averaging only 0.34% per year from 1973 to 1995, the acceleration of TFP to 0.99% suggests massive improvements in technology and increases in the efficiency of production. While the resurgence in TFP growth in the 1990s has yet

[25]Table 2 also presents preliminary results for the more recent period 1995-99, where the 1999 numbers are based on the estimation procedure described in Appendix E, rather than the detailed model described above. The results for 1995-98 and 1995-99 are quite similar; we focus our discussion on the period 1995-98.

[26]See Katz and Krueger (1999) for explanations for the strong performance of the U.S. labor market, including demographic shifts toward a more mature labor force, a rise in the prison age population, improved efficiency in labor markets, and the "weak backbone hypothesis" of worker restraint.

to surpass periods of the 1960s and early 1970s, more rapid TFP growth is critical for sustained growth at higher rates.

Charts 5 and 6 highlight the rising contributions of information technology (IT) outputs to U.S. economic growth. Chart 5 shows the breakdown between IT and non-IT outputs for various sub-periods from 1959 to 1998, while Chart 6 decomposes the contribution of IT outputs into its components. Although the role of IT has steadily increased, Chart 5 shows that the recent investment and consumption surge nearly doubled the output contribution of IT for 1995-98 relative to 1990-95. Chart 6 shows that computer investment is the largest single IT contributor in the late 1990s, and that consumption of computers and software is becoming increasingly important as a source of output growth.

Charts 7 and 8 present a similar decomposition of the role of IT as an input into production, where the contribution is rising even more dramatically. Chart 7 shows that the capital and consumers' durable contribution from IT increased rapidly in the late 1990s, and now accounts for more two-fifths of the total growth contribution from broadly defined capital. Chart 8 shows that computer hardware is also the single largest IT contributor on the input side, which reflects the growing share and rapid growth rates of the late 1990s.

The contribution of computers, software, and communications equipment presents a different picture from Jorgenson and Stiroh (1999) for both data and methodological reasons. First, the BEA benchmark revision has classified software as an investment good. While software is growing more slowly than computers, the substantial nominal share of software services has raised the contribution of information technology. Second, we have added communications equipment, also a slower growing component of capital services, with similar effects. Third, we now incorporate asset-specific revaluation terms in all rental price estimates. Since the acquisition prices of computers are steadily falling, asset-specific revaluation terms have raised the estimated service price and increased the share of computer services. Finally, we have modified our timing convention and now assume that capital services from individual assets are proportional to the average of the current and lagged stock. For assets with relatively short service lives like IT, this is a more reasonable assumption than in our earlier work, which assumed that it took a full year for new investment to become productive.[27]

This large increase in the growth contribution of computers and software is consistent with recent estimates by Oliner and Sichel (2000), although their

[27] We are indebted to Dan Sichel for very helpful discussions of this timing convention.

estimate of contribution is somewhat larger. They report that computer hardware and software contributed 0.93 percentage points to growth for 1996-99, while communications contributed another 0.15. The discrepancy primarily reflects our broader output concept, which lowers the input share of these high-tech assets, and also minor differences in tax parameters and stock estimates. Whelan (1999) also reports a larger growth contribution of 0.82 percentage points from computer hardware for 1996-98. The discrepancy also reflects our broader output concept. In addition, Whelan (1999) introduces a new methodology to account for retirement and support costs that generates a considerably larger capital stock and raises the input share and the growth contribution from computer capital.

Despite differences in methodology and data sources among studies, a consensus is building that computers are having a substantial impact on economic growth.[28] What is driving the increase in the contributions of computers, software, and communications equipment? As we argued in Jorgenson and Stiroh (1999), price changes lead to substitution toward capital services with lower relative prices. Firms and consumers are responding to relative price changes.

Table 1 shows the acquisition price of computer investment fell nearly 28% per year, the price of software fell 2.2%, and the price of communications equipment fell 1.7% during the period 1995-98, while other output prices rose 2.0%. In response to these price changes, firms accumulated computers, software, and communications equipment more rapidly than other forms of capital. Investment other than information technology actually declined as a proportion of private domestic product. The story of household substitution toward computers and software is similar. These substitutions suggest that gains of the computer revolution accrue to firms and households that are adept at restructuring activities to respond to these relative price changes.

Average Labor Productivity Growth. To provide a different perspective on the sources of economic growth we can focus on ALP growth. By simple arithmetic, output growth equals the sum of hours growth and growth in labor productivity.[29] Table 3 shows the output breakdown between growth in hours and ALP for the same periods as in Table 2. For the period 1959-1998, ALP growth was the predominant determinant of output growth, increasing just over 2% per year for 1959-98, while hours increased about 1.6% per year. We then examine the changing importance of the factors determining ALP growth. As

[28] Oliner and Sichel (2000) provide a detailed comparison of the results across several studies of computers and economic growth.

[29] See Krugman (1997) and Blinder (1997) for a discussion of the usefulness of this relationship.

shown in Equation (3), ALP growth depends on a capital deepening effect, a labor quality effect, and a TFP effect.

Chart 9 shows the importance of each factor, revealing the well-known productivity slowdown of the 1970s and 1980s, and highlighting the acceleration of labor productivity growth in the late 1990s. The slowdown through 1990 reflects less capital deepening, declining labor quality growth, and decelerating growth in TFP. The growth of ALP slipped further during the early 1990s with the serious slump in capital deepening only partly offset by a revival in the growth of labor quality and an up-tick in TFP growth. Slow growth in hours combined with slow ALP growth during 1990-95 to produce a further slide in the growth of output. This stands out from previous cyclical recoveries during the postwar period, when output growth accelerated during the recovery, powered by more rapid hours and ALP growth.

For the most recent period of 1995-98, strong output growth reflects growth in labor hours and ALP almost equally. Comparing 1990-95 to 1995-98, output growth accelerated by nearly 2 percentage points due to a 1 percentage point increase in hours worked, and a 1.0 percentage point increase in ALP growth.[30] Chart 9 shows the acceleration in ALP growth is due to capital deepening from the investment boom, as well as faster TFP growth. Capital deepening contributed 0.49 percentage points to the acceleration in ALP growth, while acceleration in TFP growth added 0.63 percentage points. Growth in labor quality slowed somewhat as growth in hours accelerated. This reflects the falling unemployment rate and tightening of labor markets as more workers with relatively low marginal products were drawn into the workforce. Oliner and Sichel (2000) also show a decline in the growth contribution of labor quality in the late 1990s, from 0.44 for 1991-95 to 0.31 for 1996-99.

Our decomposition also throws some light on the hypothesis advanced by Gordon (1999b), who argues the vast majority of recent ALP gains are due to the production of IT, particularly computers, rather than the use of IT. As we have already pointed out, more efficient IT-production generates aggregate TFP growth as more computing power is produced from the same inputs, while IT-use affects ALP growth via capital deepening. In recent years, acceleration of TFP growth is a slightly more important factor in the acceleration of ALP growth than capital deepening. Efficiency gains in computer production are important part of aggregate TFP growth, as Gordon's results on ALP suggest. We return to this issue in Section III.

[30] BLS (2000) shows similar trends for the business sector with hours growth increasing from 1.2% for 1990-95 to 2.3% for 1995-98, while ALP increased from 1.58% to 2.63%.

Total Factor Productivity Growth. Finally, we consider the remarkable performance of U.S. TFP growth in recent years. After maintaining an average rate of 0.33% for the period 1973-90, TFP growth rose to 0.36% for 1990-95 and then vaulted to 0.99% per year for 1995-98. This jump is a major source of growth in output and ALP for the U.S. economy (Charts 4 and 9). While TFP growth for the 1990s has yet to attain the peaks of some periods in the golden age of the 1960s and early 1970s, the recent acceleration suggests that the U.S. economy may be recuperating form the anemic productivity growth of the past two decades. Of course, caution is warranted until more historical experience is available.

As early as Domar (1961), economists have utilized a multi-industry model of the economy to trace aggregate productivity growth to its sources at the level of individual industries. Jorgenson, Gollop, and Fraumeni (1987) and Jorgenson (1990) have employed this model to identify the industry-level sources of growth. More recently, Gullickson and Harper (1999) and Jorgenson and Stiroh (2000) have used the model for similar purposes. We postpone more detailed consideration of the sources of TFP growth until we have examined the implications of the recent growth resurgence for intermediate-term projections.

Alternative Growth Accounting Estimates

Tables 1 through 3 and Charts 1 through 9 report our primary results using the official data published in the NIPA. As we have already noted, however, there is reason to believe that the rates of inflation in official price indices for certain high-tech assets, notably software and telecommunications equipment, may be overstated. Moulton, Parker, and Seskin (1999) and Parker and Grimm (2000), for example, report that only the pre-packaged portion of software investment is deflated with a constant-quality deflator. Own-account software is deflated with an input cost index and custom software is deflated with a weighted average of the prepackaged and own-account deflator. Similarly, BEA reports that in the communications equipment category, only telephone switching equipment is deflated with a constant-quality, hedonic deflator.

This subsection incorporates alternative price series for software and communications equipment and examines the impact on the estimates of U.S. economic growth and its sources. Table 4 presents growth accounting results under three different scenarios. The Base Case repeats the estimates from Table 2, which are based on official NIPA price data. Two additional cases, Moderate Price Decline and Rapid Price Decline, incorporate price series for software and

communications equipment that show faster price declines and correspondingly more rapid real investment growth.[31]

The Moderate Price Decline case assumes that prepackaged software prices are appropriate for all types of private software investment, including custom and business own-account software. Since the index for prepackaged software is based on explicit quality adjustments, it falls much faster than the prices of custom and own-account software, -10.1% vs. 0.4% and 4.1% respectively, for the full period 1959-98 according to Parker and Grimm (2000). For communications equipment, the data are more limited and we assume prices fell 10.7% per year throughout the entire period. This estimate is the average annual "smoothed" decline for digital switching equipment for 1985-96 reported by Grimm (1997). While this series may not be appropriate for all types of communications equipment, it exploits the best available information.

The Rapid Price Decline case assumes that software prices fell 16% per year for 1959-98, the rate of quality-adjusted price decline reported by Brynjolfsson and Kemerer (1996) for microcomputer spreadsheets for 1987-92. This is a slightly faster decline than the –15% for 1986-91 estimated by Gandal (1994), and considerably faster than the 3% annual decline for word processors, spreadsheets, and databases for 1987-93 reported by Oliner and Sichel (1994). For communications equipment, we used estimates from the most recent period from Grimm (1997), who reports a decline of 17.9% per year for 1992-96.

While this exercise necessarily involves some arbitrary choices, the estimates incorporate the limited data now available and provide a valuable perspective on the crucial importance of accounting for quality change in the prices of investment goods. Comparisons among the three cases are useful in suggesting the range of uncertainty currently confronting analysts of U.S. economic growth.

Before discussing the empirical results, it is worthwhile to emphasize that more rapid price decline for information technology has two direct effects on the sources of growth, and one indirect effect. The alternative investment deflators raise real output growth by reallocating nominal growth away from prices and towards quantities. This also increases the growth rate of capital stock, since there are larger investment quantities in each year. More rapid price declines also give greater weight to capital services from information technology.

[31]The notion that official price deflators for investment goods omit substantial quality improvements is hardly novel. The magisterial work of Gordon (1990) successfully quantified the overstatements of rates of inflation for the prices of a wide array of investment goods, covering all producers' durable equipment in the NIPA.

The counter-balancing effects of increased output and increased input growth lead to an indirect effect on measured TFP growth. Depending on the relative shares of high-tech assets in investment and capital services, the TFP residual will increase if the output effect dominates or decrease if the effect on capital services dominates.[32] Following Solow (1957, 1960), Greenwood, Hercowitz, and Krusell (1997) omit the output effect and attribute the input effect to "investment-specific" (embodied) technical change. This must be carefully distinguished from the effects of industry-level productivity growth on TFP growth, discussed in Section IV.

Table 4 reports growth accounting results from these three scenarios—Base Case, Moderate Price Decline, and Rapid Price Decline. The results are not surprising—the more rapid the price decline for software and communications, the faster the rate of growth of output and capital services. Relative to the Base Case, output growth increases by 0.16 percentage points per year for 1995-98 in the Moderate Price Decline case and by 0.34 percentage points in the Rapid Price Decline case. Capital input growth shows slightly larger increases across the three cases. Clearly, constant-quality price indexes for information technology are essential for further progress in understanding the growth impact of high-tech investment.

The acceleration in output and input growth reflects the increased contributions from IT, as well as the effect on the TFP residual. In particular, the output contribution from software for 1995-98 increases from 0.21 percentage points in the Base Case to 0.29 percentage points under Moderate Price Decline to 0.40 percentage points with Rapid Price Decline. Similarly, the capital services contribution for software increase from 0.19 to 0.29 to 0.45 percentage points. The contribution of communications equipment shows similar changes. Residual TFP growth falls slightly during the 1990s, as the input effect outweighs the output effect, due to the large capital services shares of IT.

This exercise illustrates the sensitivity of the sources of growth to alternative price indexes for information technology. We do not propose to argue the two alternative cases are more nearly correct than the Base Case with the official prices from NIPA. Given the paucity of quality-adjusted price data on high-tech equipment, we simply do not know. Rather, we have tried to highlight the importance of correctly measuring prices and quantities to understand the dynamic forces driving U.S. economic growth. As high-tech assets continue to proliferate through the economy and other investment goods become increasingly dependent on electronic components, these measurement issues will

[32] This point was originally made by Jorgenson (1966); Hulten (2000) provides a recent review.

become increasingly important. While the task that lies ahead of us will be onerous, the creation of quality-adjusted price indexes for all high-tech assets deserves top priority.

Decomposition of TFP Estimates

We next consider the role of high-tech industries as a source of continued TFP growth. As discussed above, increased output of high-tech investment goods has made important contributions to aggregate growth.[33] CEA (2000) allocates annual TFP growth of 0.39 percentage points to the computer production, while Oliner and Sichel (2000) allocate 0.47 percentage points to the production of computers and computer-related semiconductor production for the period 1995-99.

We employ a methodology based on the price "dual" approach to measurement of productivity at the industry level. Anticipating our complete industry analysis Section IV, below, it is worthwhile to spell out the decomposition of TFP growth by industry. Using the Domar approach to aggregation, industry-level productivity growth is weighted by the ratio of the gross output of each industry to aggregate value-added to estimate the industry contribution to aggregate TFP growth. In the dual approach, the rate of productivity growth is measured as the decline in the price of output, plus a weighted average of the growth rates of input prices.

In the case of computer production, this expression is dominated by two terms; namely, the price of computers and the price of semi-conductors, a primary intermediate inputs into the computer-producing industry. If semiconductor industry output is used only to produce computers, then its contribution to computer industry productivity growth, weighted by computer industry output, precisely cancels its independent contribution to aggregate TFP growth.[34] This independent contribution from the semiconductor industry, based on the complete Domar weighting scheme, is the value of semiconductor output divided by aggregate value added, multiplied by the rate of price decline in semi-conductors.

We report details of our TFP decomposition for 1990-95 and 1995-98 in Table 5 and summarize the IT vs. non-IT comparison in Chart 10. In our Base Case, using

[33] CEA (2000), Gordon (1999a), Jorgenson and Stiroh (1999), Oliner and Sichel (2000), Stiroh (1998), and Whelan (1999) have provided estimates.

[34] This calculation shows that the simplified model of Oliner and Sichel (2000) is a special case of the complete Domar weighting scheme used in Section IV.

official NIPA data, we estimate the production of information technology accounts for 0.44 percentage points for 1995-98, compared to 0.25 percentage points for 1990-95. This reflects the accelerating relative price changes prices due to radical shortening of the product cycle for semi-conductors.[35]

As we have already suggested, the estimates of price declines for high-tech investments in our Base Case calculations may be conservative; in fact, these estimates may be very conservative. Consider the Moderate Price Decline Case, which reflects only part of the data we would require for constant-quality estimates of the information technology price declines. This boosts the contribution of information technology to TFP growth to 0.64 percentage points, an increase of 0.20 percentage points for 1995-98. Proceeding to what may appear to be the outer limit of plausibility, but still consistent with the available evidence, we can consider the case of Rapid Price Decline. The contribution of information technology to TFP growth is now a robust 0.86 percentage points, accounting for all of TFP growth for 1995-98.

Setting the Speed Limit

We next consider the sustainability of recent U.S. growth trends over longer time horizons. Rapid output growth is highly desirable, of course, but cannot continue indefinitely if fueled by a falling unemployment rate and higher labor force participation. Output growth driven by continuing TFP improvements, on the other hand, is more likely to persist. The sustainability of growth has clear implications for government policies. Since economic growth affects tax revenues, potential government expenditures, and the long-term viability of programs like Social Security and Medicare, it is closely studied by government agencies. This section examines the impact of the recent success of the U.S. economy on official growth forecasts.

A Brief Review of Forecast Methodologies

The importance of economic growth for the U.S. government is evident in the considerable effort expended on projecting future growth. No fewer than five government agencies—the Congressional Budget Office (CBO), the Social

[35]Relative price changes in the Base Case are taken from the investment prices in Table 5. Output shares are estimated based on final demand sales available from the BEA website for computers and from Parker and Grimm (2000) for software. Investment in communications equipment is from the NIPA, and we estimate other final demand components for communications equipment using ratios relative to final demand for computers. This is an approximation necessitated by the lack of complete data of sales to final demand by detailed commodity.

Security Administration (SSA), the Office of Management and Budget (OMB), the Council of Economic Advisors (CEA), and the General Accounting Office (GAO)—report estimates of future growth for internal use or public discussion. This section briefly discusses the methodologies used by these agencies.[36]

All five agencies employ models that rest securely on neoclassical foundations. While the details and assumptions vary, all employ an aggregate production model similar to Equation (1), either explicitly or implicitly. In addition, they all incorporate demographic projections from the SSA as the basic building block for labor supply estimates. CBO (1995, 1997, 1999a, 1999b, 2000) and GAO (1995, 1996) employ an aggregate production function and describe the role of labor growth, capital accumulation, and technical progress explicitly. SSA (1992, 1996), OMB (1997, 2000), and CEA (2000) on the other hand, employ a simplified relationship where output growth equals the sum of growth in hours worked and labor productivity. Projections over longer time horizons are driven by aggregate supply with relatively little attention to business cycle fluctuations and aggregate demand effects.

Given the common framework and source data, it is not surprising that the projections are quite similar. Reporting on estimates released in 1997, Stiroh (1998b) finds that SSA and GAO projections of per capita GDP in 2025 were virtually identical, while CBO was about 9% higher due to economic feedback effects from the improving government budget situation. More recently, CBO (2000) projects real GDP growth of 2.8% and OMB (2000) projects 2.7% for 1999-2010, while CEA (2000) reports 2.8% for 1999-2007. Although the timing is slightly different—CBO projects faster growth than OMB earlier in the period and CEA reports projections only through 2007– the estimates are virtually identical. All three projections identify the recent investment boom as a contributor to rising labor productivity and capital deepening as a source of continuing economic growth. We now consider the CBO projections in greater detail.

CBO's Growth Projections

Of the five government agencies CBO utilizes a sophisticated and detailed long-run growth model of the U.S. economy.[37] The core of this model is a two-factor production function for the non-farm business sector with CBO projections based

[36] Stiroh (1998b) provides details and references to supporting documents.

[37] The five sectors – nonfarm business, farm, government, residential housing, and households and nonprofit institutions – follow the breakdown in Table 1.7 of the NIPA.

on labor force growth, national savings and investment, and exogenous TFP growth. Production function parameters are calibrated to historical data, using a Cobb-Douglas model:

(6) $$Y = A \cdot H^{0.7} \cdot K^{0.3}$$

where Y is potential output, H is potential hours worked, K is capital input, and A is potential total factor productivity.[38]

CBO projects hours worked on the basis of demographic trends with separate estimates for different age and sex classifications. These estimates incorporate SSA estimates of population growth, as well as internal CBO projections of labor force participation and hours worked for the different categories. However, CBO does use this demographic detail to identify changes in labor quality. Capital input is measured as the service flow from four types of capital stocks—producers' durable equipment excluding computers, computers, nonresidential structures, and inventories. Stocks are estimated by the perpetual inventory method and weighted by rental prices, thereby incorporating some changes in capital quality. TFP growth is projected on the basis of recent historical trends, with labor quality growth implicitly included in CBO's estimate of TFP growth.

Turning to the most recent CBO projections, reported in CBO (2000), we focus on the non-farm business sector, which drives the GDP projections and is based on the most detailed growth model. Table 6 summarizes CBO's growth rate estimates for the 1980s and 1990s, and projections for 1999-2010. We also present estimates from BLS (2000) and our results.[39]

CBO projects potential GDP growth of 3.1% for 1999-2010, up slightly from 3.0% in the 1980s and 2.9% in the 1990s. CBO expects actual GDP growth to be somewhat slower at 2.8%, as the economy moves to a sustainable, long-run growth rate. Acceleration in potential GDP growth reflects faster capital accumulation and TFP growth, partly offset by slower growth in hours worked. Projected GDP growth is 0.4% higher than earlier estimates (CBO (1999b)) due to an upward revision in capital growth (0.1%), slightly more rapid growth in hours

[38]See CBO (1995, 1997) for details on the underlying model and the adjustments for business cycle effects that lead to the potential series.

[39]Note the growth rates in Table 5 do not exactly match Table 2 due to differences in calculating growth rates. All growth rates in Table 5 follow CBO's convention of calculating discrete growth rates as $g = \left[(X_t / X_0)^{1/t} - 1\right] * 100$, while growth rates in Table 2 are calculated as $g = \left[\ln(X_t / X_0)/t\right] * 100$.

(0.1%), and faster TFP growth, reflecting the benchmark revisions of NIPA and other technical changes (0.2%).[40]

CBO's estimates for the non-farm business sector show strong potential output growth of 3.5% for 1999-2010. While projected output growth is in line with experience of the 1990s and somewhat faster than the 1980s, there are significant differences in the underlying sources. Most important, CBO projects an increasing role for capital accumulation and TFP growth over the next decade, while hours growth slows. This implies that future output growth is driven by ALP growth, rather than growth in hours worked.

CBO projects potential non-farm business ALP growth for 1999-2010 to rise to 2.3%, powered by capital deepening (3.2%) and TFP growth (1.4%). This represents a marked jump in ALP growth, relative to 1.5% in the 1980s and 1.9% in the 1990s. In considering whether the recent acceleration in ALP growth represents a trend break, CBO "gives considerable weight to the possibility that the experience of the past few years represents such a break (CBO (2000), pg. 43)." This assumption appears plausible given recent events, and low unemployment and high labor force participation make growth in hours worked a less likely source of future growth. Falling investment prices for information technology make capital deepening economically attractive, while the recent acceleration in TFP growth gives further grounds for optimistic projections.

As the investment boom continues and firms substitute toward more information technology in production, CBO has steadily revised its projected growth rates of capital upward. It is worthwhile noting just how much the role of capital accumulation has grown in successive CBO projections, rising from a projected growth rate of 3.6% in January 1999 (CBO (1999a)) to 4.1% in July 1999 (CBO (1999b)) to 4.4% in January 2000 (CBO (2000)). This reflects the inclusion of relatively fast-growing software investment in the benchmark revision of NIPA, but also extrapolates recent investment patterns.

Similarly, CBO has raised its projected rate of TFP growth in successive estimates—from 1.0% in January 1999 to 1.1% in July 1999 to 1.4% in January 2000.[41] These upward revisions reflect methodological changes in how CBO accounts for the rapid price declines in investment, particularly computers, which added 0.2%. In addition, CBO adjustments for the benchmark revision of NIPA contributed another 0.1%.

[40] See CBO (2000, pg. 25 and pg. 43) for details.

[41] Earlier upward revisions to TFP growth primarily reflect "technical adjustment...for methodological changes to various price indexes" and "increased TFP projections (CBO (1999b), pg. 3)."

Table 6 also reports our own estimates of growth for roughly comparable periods. While the time periods are not precisely identical, our results are similar to CBO's. We estimate slightly faster growth during the 1980s, due to rapidly growing CD services, but slightly lower rates of capital accumulation due to our broader measure of capital. Our growth of hours worked is higher, since we omit the cyclical adjustments made by CBO to develop their potential series.[42] Finally, our TFP growth rates are considerably lower, due to our labor quality adjustments and inclusion of consumers' durables. If we were to drop the labor quality adjustment, our estimate would rise to 1.0% per year from 1990 to 1998, compared to 1.2% for CBO for 1990-99. The remaining difference reflects the fact that we do not include the rapid TFP growth of 1999, but do include the services of consumers' durables, which involve no growth in TFP.

Evaluating CBO's Projections

Evaluating CBO's growth projections requires an assessment of their estimates of the growth of capital, labor, and TFP. It is important to emphasize that this is not intended as a criticism of CBO, but rather a description of "best practice" in the difficult area of growth projections. We also point out comparisons between our estimates and CBO's estimates are not exact due to our broader output concept and our focus on actual series, as opposed the potential series that are the focus of CBO.

We begin with CBO's projections of potential labor input. These data, based on the hours worked from BLS and SSA demographic projections, show a decline in hours growth from 1.5% in the 1990s to 1.2% for the period 1999-2010. This slowdown reflects familiar demographic changes associated with the aging of the U.S. population. However, CBO does not explicitly estimate labor quality, so that labor composition changes are included in CBO's estimates of TFP growth and essentially held constant.

We estimate growth in labor quality of 0.57% per year for 1990-98, while our projections based on demographic trends yield a growth rate of only 0.32% for the 1998-2010 period. Assuming CBO's labor share of 0.70, this implies that a decline in the growth contribution from labor quality of about 0.18 percentage points per year over CBO's projection horizon. Since this labor quality effect is implicitly incorporated into CBO's TFP estimates, we conclude their TFP

[42]See CBO (1995) for details on the methodology for cyclical adjustments to derive the "potential" series.

projections are overstated by this 0.18 percentage points decline in the labor quality contribution.

TFP growth is perhaps the most problematical issue in long-term projections. Based on the recent experience of the U.S. economy, it appears reasonable to expect strong future productivity performance. As discussed above and shown in Table 2, TFP growth has increased markedly during the period 1995-98. However, extrapolation of this experience runs the risk of assuming that a temporary productivity spurt is a permanent change in trend.

Second, the recent acceleration of TFP growth is due in considerable part to the surge in productivity growth in industries producing IT. This makes the economy particularly vulnerable to slowing productivity growth in these industries. Computer prices have declined at extraordinary rates in recent years and it is far from obvious that this can continue. However, acceleration in the rate of decline reflects the change in the product cycle for semi-conductors, which has shifted from three years to two and may be permanent.

We conclude that CBO's projection of TFP growth is optimistic in assuming a continuation of recent productivity trends. However, we reduce this projection by only 0.18 percent per year to reflect the decline in labor quality growth, resulting in projected TFP growth of 1.22% per year. To obtain a projection of labor input growth we add labor quality growth of 0.32% per year to CBO's projection of growth in hours of 1.2% per year. Multiplying labor input growth of 1.52% per year by the CBO labor share of 0.7, we obtain a contribution of labor input of 1.06%.

CBO's projected annual growth of capital input of 4.4% is higher than in any other decade, and 0.8% higher than in the 1990s. This projection extrapolates recent increases in the relative importance of computers, software, and communications equipment. Continuing rapid capital accumulation is also predicated on the persistence of high rates of decline in asset prices, resulting from rapid productivity growth in the IT producing sectors. Any attenuation in this rate of decline would produce a double whammy—less TFP growth and reduced capital deepening.

Relative to historical trends, CBO's capital input growth projection of 4.4% seems out of line with the projected growth of potential output of 3.5%. During the 1980s capital growth exceeded output growth by 0.4%, according to their estimates, or 0.1% by our estimates. In the 1990s capital growth exceeded output growth by only 0.2%, again according to their estimates, and 0.1% by our

estimates. This difference jumps to 0.9% for the period of CBO's projections, 1999-2010.

Revising the growth of capital input downward to reflect the difference between the growth of output and the growth of capital input during the period 1995-98 of 0.2% would reduce the CBO's projected output growth to 3.34% per year. This is the sum of the projected growth of TFP of 1.22% per year, the contribution of labor input of 1.06% per year, and the contribution of capital input of 1.06% per year. This is a very modest reduction in output growth from CBO's projection of 3.5% per year and can be attributed to the omission of a projected decline in labor quality growth.

We conclude that CBO's projections are consistent with the evidence they present, as well as our own analysis of recent trends. We must emphasize, however, that any slowdown in technical progress in information technology could have a major impact on potential growth. Working through both output and input channels, the U.S. economy has become highly dependent on information technology as the driving force in continued growth. Should productivity growth in these industries falter, the projections we have reviewed could be overly optimistic.

Industry Productivity

We have explored the sources of U.S. economic growth at the aggregate level and demonstrated that accelerated TFP growth is an important contributor to the recent growth resurgence. Aggregate TFP gains—the ability to produce more output from the same inputs—reflects the evolution of the production structure at the plant or firm level in response to technological changes, managerial choices, and economic shocks. These firm- and industry-level changes then cumulate to determine aggregate TFP growth. We now turn our attention to industry data to trace aggregate TFP growth to its sources in the productivity growth of individual industries, as well as reallocations of output and inputs among industries.

Our approach utilizes the framework of Jorgenson, Gollop, and Fraumeni (1987) for quantifying the sources of economic growth for U.S. industries. The industry definitions and data sources have been brought up-to-date. The methodology of Jorgenson, Gollop, and Fraumeni for aggregating over industries is based on Domar's (1961) approach to aggregation. Jorgenson and Stiroh (2000) have presented summary data from our work; other recent studies of industry-level productivity growth include BLS (1999), Corrado and Slifman (1999), and

Gullickson and Harper (1999). The remainder of this section summarizes our methodology and discusses the results.

Methodology

As with the aggregate production model discussed in Section II, we begin with an industry-level production model for each industry. A crucial distinction, however, is that industry output Qi is measured using a "gross output" concept, which includes output sold to final demand as well as output sold to other industries as intermediate goods. Similarly, inputs include all production inputs, including capital services Ki and labor services Li, as well as intermediate inputs, energy Ei and materials Mi, purchased from other industries.[43] Our model is based on the industry production function:

$$(7) \qquad Q_i = A_i \cdot X_i(K_i, L_i, E_i, M_i)$$

where time subscripts have been suppressed for clarity.

We can derive a growth accounting equation similar to Equation (2) for each industry to measure the sources of economic growth for individual industries. The key difference is the use of gross output and an explicit accounting of the growth contribution of intermediate inputs purchased from other industries. This yields:

$$(8) \qquad \Delta \ln Q_i = \overline{w}_{K_i} \Delta \ln K_i + \overline{w}_{L_i} \Delta \ln L_i + \overline{w}_{E_i} \Delta \ln E_i + \overline{w}_{M_i} \Delta \ln M_i + \Delta \ln A_i$$

where $\overline{w}_i$ is the average share of the subscripted input in the ith industry and the assumptions of constant returns to scale and competitive markets imply $\overline{w}_{K_i} + \overline{w}_{L_i} + \overline{w}_{E_i} + \overline{w}_{M_i} = 1$.

The augmentation factor DlnAi represents the growth in output not explained by input growth and is conceptually analogous to the TFP concept used above in the aggregate accounts. It represents efficiency gains, technological progress, scale economies, and measurement errors that allow more measured gross output to be produced from the same set of measured inputs. We refer to this term as industry productivity or simply productivity to distinguish it from TFP, which is estimated from a value-added concept of output.[44]

[43]This is analogous to the sectoral output concept used by BLS. See Gullickson and Harper (1999), particularly pp. 49-53 for a review of the concepts and terminology used by the BLS.

[44]BLS refers to this concept as *multi-factor productivity* (MFP).

Domar (1961) first developed an internally consistent methodology that linked industry-level productivity growth in Equation (8) with aggregate TFP growth in Equation (2). He showed that aggregate TFP growth can be expressed as a weighted average of industry productivity growth:

(9)

$$\Delta \ln A = \sum_{i=1}^{37} \overline{w}_i \cdot \Delta \ln A_i, \quad \overline{w}_i = \frac{1}{2}\left(\frac{P_{i,t} \cdot Q_{i,t}}{P_{Y,t} \cdot Y_t} + \frac{P_{i,t-1} \cdot Q_{i,t-1}}{P_{Y,t-1} \cdot Y_{t-1}} \right)$$

where $\overline{w}_i$ is the "Domar weight", Pi◊Qi is current dollar gross output in sector i, and PY◊Y is current dollar aggregate value-added. This simplified version of the aggregation formula given by Jorgenson, Gollop, and Fraumeni (1987), excludes re-allocations of value added, capital input, and labor input by sector. Jorgenson and Stiroh (2000) show that these terms are negligible for the period 1958-1996, which is consistent with the results of Jorgenson, Gollop, and Fraumeni (1987) and Jorgenson (1990) for periods of similar duration.

Domar weights have the notable feature that they do not sum to unity. This reflects the different output concepts used at the aggregate and industry levels in Equations (1) and (7), respectively. At the aggregate level, only primary inputs are included, while both primary and intermediate inputs are included in the industry production functions. For the typical industry, gross output considerably exceeds value added, so the sum of gross output across industries exceeds the sum of value added. This weighting methodology implies that economy-wide TFP growth can grow faster than productivity in any industry, since productivity gains are magnified as they work their way through the production process.[45]

In addition to providing an internally consistent aggregation framework, industry-level gross output allows an explicit role for intermediate goods as a source of industry growth. For example, Triplett (1996) shows that a substantial portion of the price declines in computer output can be traced to steep price declines in semi-conductors, the major intermediate input in the computer-producing industry. Price declines in semiconductors reflect technological progress—Moore's law in action. This should be measured as productivity growth in the industry that produces semiconductors. By correctly accounting

[45]Jorgenson, Gollop, and Fraumeni (1987), particularly Chapter 2, provide details and earlier references; Gullickson and Harper (1999, pg. 50) discuss how aggregate productivity can exceed industry productivity in the Domar weighting scheme.

for the quantity and quality of intermediate inputs, the gross output concept allows aggregate TFP gains to be correctly allocated among industries.

Data Sources

Our primary data include a set of inter-industry transactions accounts developed by the Employment Projections office at the BLS. These data cover a relatively short time period from 1977 to 1995. We linked the BLS estimates to industry-level estimates back to 1958, described by Stiroh (1998a), and extrapolated to 1996 using current BLS and BEA industry data.[46] This generated a time series for 1958 to 1996 for 37 industries, at roughly the two-digit Standard Industrial Classification (SIC) level, including Private Households and General Government.[47] Table 7 lists the 37 industries, the relative size in terms of 1996 value-added and gross output, and the underlying SIC codes for each industry.

Before proceeding to the empirical results, we should point out two limitations of this industry-level analysis. Due to the long lag in obtaining detailed inter-industry transactions, investment, and output data by industry, our industry data are not consistent with the BEA benchmark revision of NIPA published in December 1999; they correspond to the NIPA produced by BEA in November 1997. As a consequence, they are not directly comparable to the aggregate data described in Tables 1 through 6. Since the impact of the benchmark revision was to raise output and aggregate TFP growth, it is not surprising that the industry data show slower output and productivity growth. Second, our estimates of rental prices for all assets in this industry analysis are based on the industry-wide asset revaluation terms, as in Stiroh (1998a). They are not directly comparable to the aggregate data on capital input, where asset-specific revaluation terms are included in the rental price estimates. The use of industry-wide revaluation terms tends to reduce the growth in capital services since assets with falling relative prices, such as computers, have large service prices and rapid accumulation rates.

Empirical Results

Sources of Industry Growth. Table 8 reports estimates of the components of Equation (8) for the period 1958-1996. For each industry, we show the growth in output, the contribution of each input (defined as the nominal share-weighted

[46] We are grateful to Mun Ho for his extensive contributions to the construction of the industry data.

[47] Appendix D provides details on the component data sources and linking procedures.

growth rate of the input), and productivity growth. We also report average labor productivity (ALP) growth, defined as real gross output per hour worked, and the Domar weights calculated from Equation (9). We focus the discussion of our results on industry productivity and ALP growth.

Industry productivity growth was the highest in two high-tech industries, Industrial Machinery and Equipment, and Electronic and Electric Equipment, at 1.5% and 2.0% per year, respectively. Industrial Machinery includes the production of computer equipment (SIC #357) and Electronic Equipment includes the production of semiconductors(SIC #3674) and communications equipment (SIC #366). The enormous technological progress in the production of these high-tech capital goods has generated falling prices and productivity growth, and fueled the substitution towards information technology.

An important feature of these data is that we can isolate productivity growth for industries that produce intermediate goods, for example, Electronic and Electric Equipment.[48] Consider the contrast between computer production and semiconductor production. Computers are part of final demand, sold as consumption and investment goods, and can be identified in the aggregate data, as we did in Table 2. Semiconductors, on the other hand, do not appear at the aggregate level, since they are sold almost entirely as an input to computers, telecommunications equipment, and an increasingly broad range of other products such as machine tools, automobiles, and virtually all recent vintages of appliances. Nonetheless, improved semiconductor production is an important source of aggregate TFP growth since it is ultimately responsible for the lower prices and improved quality of goods like computers produced for final demand.

The enormous price declines in computer equipment and the prominent role of investment in computers in the GDP accounts have led Gordon (1999b), Whelan (1999), and others to emphasize technological progress in the production of computers. Triplett (1996), however, quantifies the role of semiconductors as an intermediate input and estimates that falling semiconductor prices may account for virtually all of the relative price declines in computer equipment. He concludes, "productivity in the computer industry palls beside the enormous increases in productivity in the semiconductor industry (Triplett (1996), pg. 137)."[49]

[48]Our industry classification is too broad to isolate the role of semiconductors.

[49]This conclusion rests critically on the input share of semiconductors in the computer industry. Triplett reports Census data estimates of this share at 15% for 1978-94, but states industry sources estimate this share to be closer to 45%. This has an important impact on his results. At one end of the spectrum, if no account is made for semiconductor price declines, the relative productivity in

The decline in prices of semiconductors is reflected in the prices of intermediate input into the computer industry, effectively moving productivity away from computers and toward semiconductor production. Building on this observation, Oliner and Sichel (2000) present a model that includes three sectors—semiconductor production, computer production, and other goods—and shows that semiconductors productivity is substantially more important than computer productivity. Our complete industry framework with Domar aggregation over all industries captures the contributions of productivity growth from all industries.

The impact of intermediate inputs can be seen in Table 8 in the large contribution of material inputs in the Industrial Machinery industry. Since a substantial portion of these inputs consists of semiconductors purchased from the Electronic Equipment industry, productivity gains that lower the price of semiconductors increase the flow of intermediate inputs into the Industrial Machinery industry. By correctly accounting for these inputs, industry productivity growth in the Industrial Machinery industry falls, and we can rightly allocate technological progress to the Electronic Equipment industry, which produces semiconductors. While this type of industry reallocation does not affect aggregate productivity growth, it is important to identify the sources of productivity growth and allocate this among industries in order to assess the sustainability of the recent acceleration.

The two high-tech industries also show high rates of average labor productivity (ALP) growth of 3.1% and 4.1% per year. This reflects an underlying relationship similar to Equation (3) for the aggregate data, where industry ALP growth reflects industry productivity growth, labor quality growth, and increases in input intensity, including increases in capital as well as intermediate inputs per hour worked. As implied by Table 8, these industries showed rapid accumulation of capital and intermediate inputs, which raised ALP growth above productivity growth. It is also worthwhile to note that Communications, another high-tech industry, shows ALP growth much faster than industry productivity growth due to the rapid accumulation of inputs, notably intermediate materials. These results highlight the crucial importance of accounting for all inputs when examining the sources of industry growth.

Productivity growth in information technology provides a final perspective on the conclusions of Greenwood, Hercowitz, and Krusell (1997) and Hercowitz (1998). They argue that some 60% of postwar U.S. growth can be attributed to

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computer equipment increases 9.1% for 1978-94. Assuming a 15% share for semiconductors causes this to fall to 9%; assuming a 45% share causes a fall to 1%.

investment-specific (embodied) productivity growth, which they distinguish from input accumulation and (disembodied) productivity growth. As evidence, they note the relative price of equipment in the U.S. has fallen 3% per year, which they interpret as evidence of technical change that affect capital goods, but not consumption goods. Our decomposition, however, reveals that declines in the prices of investment goods are the consequence of improvements in industry (disembodied) productivity. Domar aggregation shows how these improvements contribute directly to aggregate TFP growth. There is no separate role for investment-specific technical change.

Other industries that show relatively strong productivity growth include Agriculture, Textile Mill Products, Rubber and Plastic, Instruments, Trade. All of these industries experienced productivity growth in the 1.0% per year range, and ALP growth in the 2-3% range. Industries with the slowest productivity growth include Petroleum and Gas, Construction, Printing and Publishing, and Government Enterprises, all of which showed a declines in productivity of nearly 0.5% per year.

It is worth emphasizing that nine industries showed negative productivity growth for the entire period, a counter-intuitive result, if we were to interpret productivity growth solely as technological progress. It is difficult to envision technology steadily worsening for a period of nearly 40 years as implied by these estimates. The perplexing phenomenon of negative technical progress was a primary motivation for the work of Corrado and Slifman (1999) and Gullickson and Harper (1999), who suggest persistent measurement problems as a plausible explanation. Corrado and Slifman (1999) conclude, "a more likely statistical explanation for the implausible productivity, profitability, and price trends…is that they reflect problems in measuring prices (pg. 331)." If prices are systematically overstated because quality change is not accurately measured, then output and productivity are correspondingly understated. We do not pursue this idea here, but simply point out that measurement problems are considered a reasonable explanation by some statistical agencies.[50]

An alternative interpretation for negative productivity growth is the possibility of declines in efficiency that have no association with technology. These might include lower quality of management and worsening of industrial organization through the growth of barriers to entry. This appears to be plausible explanation, given the widespread occurrence of negative productivity growth for extended periods of time. Until more careful research linking firm- and plant-level

[50]Dean (1999) summarizes the BLS view on this issue. McGuckin and Stiroh (2000) attempt to quantify the magnitude of the potential mismeasurement effects.

productivity to industry productivity estimates has been done, it would be premature to leap to the conclusion that estimates of economic performance should be adjusted so as to eliminate negative productivity growth rates, wherever they occur.

Low productivity growth rates are surprising in light of the fact that many of the affected industries are heavy investors in information technology. Stiroh (1998a), for example, reports nearly 80% of computer investment in the early 1990s was in three service-related industries, Trade, FIRE, and Services. Triplett (1999) reports a high concentration in service industries using the BEA's capital use survey. The apparent combination of slow productivity growth and heavy computer-use remains an important obstacle for new economy proponents who argue that the use of information technology is fundamentally changing business practices and raising productivity throughout the U.S. economy.

Comparison to Other Results. Before proceeding to the Domar aggregation results, it is useful to compare these results to three other recent studies—BLS (1999), Corrado and Slifman (1999) and Gullickson and Harper (1999). BLS (1999) reports industry productivity growth ("industry multifactor productivity" in their terminology) for 19 manufacturing industry for 1949-96. Corrado and Slifman (1999) report estimates of ALP growth for selected one- and two-digit SIC industries for the period 1977-97. Gullickson and Harper (1999) report industry productivity growth for certain one and two-digit SIC industries based on two output series for the period 1947-1992. Similar to BLS (1999), Gullickson and Harper use a "sectoral output" concept estimated by the Employment Projections staff at BLS and also, for 1977-92, use BEA's gross output series, "adjusted for consistency."[51] Note that none of these studies reflect the BEA benchmark revision of NIPA.

Time period, industry classification, and methodological differences make a definitive reconciliation to our results impossible. For example, BLS (1999) reports detailed manufacturing industries; Corrado and Slifman (1999) use a value-added concept, BEA's "gross product originating," for output; Gullickson and Harper (1999) use the same data sources as we do, but make different adjustments for consistency and do not account for labor quality growth. Nonetheless, it is useful to compare broad trends over similar time periods to assess the robustness of our findings.

We first consider the ALP estimates from Corrado and Slifman (1999). We can compare similar time periods, but there are relatively few overlapping industries

[51] See Gullickson and Harper (1999), particularly pp. 55-56, for details

since our industry breakdown focuses on manufacturing industries, while they provide details primarily for service industries. For comparable industries, however, the results are quite similar. For seven industries with comparable definitions, five show differences in ALP growth of less than 0.25% when we compare our estimates for 1977-96 to Corrado and Slifman's estimates for 1977-97 (Corrado and Slifman (1999, Table 2).[52] Our ALP growth rates for Communication and Trade are below theirs by 1.3% and 0.4%, respectively, for these periods.

Our productivity estimates for 1977-92 for the majority of industries are similar to those of Gullickson and Harper (1999). The range of discrepancies is somewhat greater due to the difficulty of linking the various data sets needed to estimate intermediate inputs and industry productivity growth. For 7 of the 11 comparable industries productivity differences are below 0.5%, while we found larger discrepancies for Metal Mining, Coal Mining, Petroleum and Gas, and Services.[53] Similar differences can also be seen in Gullickson and Harper's comparison of productivity growth estimated from the BLS and BEA gross output series, where they find differences of 0.5 percentage points or more in 17 out of 40 industries and aggregates. Methodological differences, such as the inclusion of labor quality growth in our estimates of labor input growth, contribute to this divergence, as do different methods for linking data sets.

Neither Corrado and Slifman (1999) nor Gullickson and Harper (1999) break out ALP growth or industry productivity growth for detailed manufacturing industries. To gauge these results, we have compared our manufacturing results to the manufacturing industry estimates in BLS (1999). For the 18 industries that are comparable, ten showed productivity differences of less than 0.25% for 1979-96; two showed differences between 0.25% and 0.5%; and the remaining six industries, Textile Mills, Lumber and Wood, Petroleum Refining, Leather, Stone, Clay and Glass, and Instruments, showed differences greater than 0.5.[54]

Domar Aggregation. We now turn to the aggregation of industry productivity growth described by Equation (9). This is not directly comparable to our estimates of aggregate productivity, due to different vintages of data and a broader definition of output. Nonetheless, it is useful to quantify an industry's

[52]These five industries are Agriculture, Construction, Transportation, FIRE and Services. Note that our estimates for 1977-1996 are not given in Table 10.

[53]These seven other industries that are comparable are Agriculture, Nonmetallic Mining, Construction, Transportation, Communications, Trade, and FIRE.

[54]The 10 industries with small differences are Food Products, Apparel, Furniture and Fixtures, Paper Products, Printing and Publishing, Chemical Products, Primary Metals, Industrial and Commercial Machinery, Electronic and Electric Machinery, and Miscellaneous Manufacturing. The two industries with slightly larger differences are Rubber and Plastic, and Fabricated Metals.

contribution to aggregate TFP growth and to trace aggregate productivity growth back to its sources at the level of the individual industry. These results update the earlier estimates of Jorgenson, Gollop, and Fraumeni (1987). Gordon (1999b) presents a similar decomposition for ALP growth, although he focuses exclusively on the contribution from computer production.

We present our estimates of each industry's contribution to aggregate TFP growth for the period 1958-96 in Chart 11. This follows Equation (9) by weighting industry productivity growth by the "Domar weight," defined as industry gross output divided by aggregate value-added. Summing across industries gives an estimate of aggregate TFP growth of 0.48 for 1958-96. This is lower than the number implied by Table 2 for two reasons. First, the data are prior to the BEA benchmark revision, which raised output and TFP growth. Second, these estimates include a broader output concept that includes Government Enterprises, which we estimate has negative industry productivity growth, and the General Government, which has zero productivity growth by definition. The estimate is consistent, however, with the estimates in Ho, Jorgenson, and Stiroh (1999) and Jorgenson and Stiroh (1999), which are based on the same vintage of data.

The most striking feature of Chart 11 is the wide range of industry contributions. Trade, Industrial Machinery, and Electronic Equipment make the largest contribution, although for different reasons. Trade has solid, but not exceptionally strong productivity growth of almost 1% per year, but makes the largest contribution due to its large relative size; Trade receives a Domar weight of nearly 0.20. Industrial Machinery and Electronic Equipment, on the other hand, make important contributions due to their rapid productivity growth, 1.5% and 2.0%, respectively, in spite of their relative small sizes with Domar weights of 0.05 and 0.04, respectively. An industry's contribution to aggregate productivity growth depends on both productivity performance and relative size.

Chart 11 also highlights the impact of the nine industries that experienced negative productivity growth over this period. Again, both performance and relative size matter. Services makes a negative contribution of 0.07 due to its large weight and productivity growth of –0.19%. Construction, on the other hand, shows even slower industry productivity growth, –0.44% per year, but makes a smaller negative contribution, since it is so much smaller than Services. We can also do a "thought experiment" similar to Corrado and Slifman (1999) and Gullickson and Harper (1999) and imagine that productivity growth is zero in these nine industries rather than negative. By zeroing out the negative contributions, we find aggregate TFP growth would have been 0.22% higher, an

increase of nearly half.[55] Clearly, negative productivity growth in these industries is an important part of the aggregate productivity story.

Finally, these data enable us to provide some new perspective on an argument made by Gordon (1999b), who decomposes trend-adjusted ALP growth into a portion due to computer-production and a residual portion for the rest of the economy.[56] He finds the former accounts for virtually all of the productivity acceleration since 1997. While we cannot comment directly on his empirical estimates since our industry data end in 1996 and we examine TFP growth rather than ALP growth, we can point to an important qualification to his argument. The U.S. economy is made up of industries with both positive and negative productivity growth rates, so that comparing one industry to the aggregate of all others necessarily involves aggregation over off-setting productivity trends. The fact that this aggregate does not show net productivity growth does not entail the absence of gains in productivity in any of the component industries, since these gains could be offset by declines in other industries.

Consider our results for 1958-96 and the importance of the negative contributions. The five industries with the largest, positive contributions—Trade, Electronic Equipment, Agriculture, Industrial Machinery, and Transport—cumulatively account for the sum across all industries, about 0.5% per year. Nonetheless, we find sizable productivity growth in some remaining industries that are offset by negative contributions in others. This logic and the prevalence of negative productivity growth rates at the industry level, in BLS (1999), Corrado and Slifman (1999), and Gullickson and Harper (1999), suggest that a similar argument could hold for ALP and for the most recent period. This raises the question of whether off-setting productivity growth rates are responsible for Gordon's finding that there is "no productivity growth in the 99 percent of the economy located outside the sector which manufactures computer hardware (Gordon (1999b, p. 1, italics in original))." Assessing the breadth of recent productivity gains and identifying the sources in productivity growth at the industry level remains an important question for future research.

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[55]This aggregate impact is smaller than that estimated by Gullickson and Harper (1999), partly because our shares differ due to the inclusion of a Household and Government industry. Also, as pointed out by Gullickson and Harper, a complete re-estimation would account for the change in intermediate inputs implied by the productivity adjustments.

[56]Oliner and Sichel (2000) argue that Gordon's conclusion is weakened by the new NIPA data released in the benchmark revision, which allow a larger role for ALP growth outside of computer production.

Conclusions

The performance of the U.S. economy in the late 1990s has been nothing short of phenomenal. After a quarter century of economic malaise, accelerating total factor productivity growth and capital deepening have led to a remarkable growth resurgence. The pessimism of the famous Solow (1987) paradox, that we see computers everywhere but in the productivity statistics, has given way to optimism of the information age. The productivity statistics, beginning in 1995, have begun to reveal a clearly discernible impact of information technology. Both labor productivity and TFP growth have jumped to rates not seen for such an extended period of time since the 1960s. While a substantial portion of these gains can be attributed to computers, there is growing evidence of similar contributions from software and communications equipment—each equal in importance to computers.

The forces shaping the information economy originate in the rapid progress of semiconductor technology—Moore's Law at work. These gains are driving down relative prices of computers, software, and communications equipment and inducing massive investments in these assets by firms and households. Technological progress and the induced capital deepening are the primary factors behind accelerating output growth in recent years. The sustainability of recent growth trends therefore hinges to a great degree on prospects for continuing progress, especially in the production of semiconductors. While this seems plausible and perhaps even likely, the contribution of high-tech assets to the growth resurgence remains subject to considerable uncertainty, owing to incomplete information on price trends for these assets.

The strong performance of the U.S. economy has not gone unnoticed. Forecasters have had to raise their projected growth rates and raise them again. The moderate speed limits set by Blinder (1997) and Krugman (1997), reflecting the best evidence available only a few years ago, have given way to the optimism of the ordinarily conservative community of official forecasters. Our review of the evidence now available suggests that the official forecasters are relying very heavily on a continuation of the acceleration in U.S. economic growth since 1995.

What are the risks to the optimistic view of future U.S. economic growth in the information age? Upward revision of growth projections seems a reasonable response as evidence accumulates of a possible break in trend productivity growth. Nonetheless, caution is warranted until productivity patterns have been observed for a longer time period. Should the pace of technological progress in high-tech industries diminish, economic growth would be hit with a double whammy—slower total factor productivity growth in important industries that

produce high-tech equipment and slower capital accumulation in other sectors that invest in and use the high-tech equipment. Both factors have made important contribution to the recent success of the U.S. economy, so that any slowdown would retard future growth potential.

At the same time we must emphasize that the uncertainty surrounding intermediate term projections has become much greater as a consequence of widening gaps in our knowledge, rather than changes in the volatility of economic activity. The excellent research that underlies estimates of prices and quantities of computer investment in NIPA has provided much needed illumination of the impact of information technology. But this is only part of the contribution of information technology to economic growth and may not be the largest part. As the role of technology continues to increase, ignorance of the most basic empirical facts about the information economy will plague researchers as well as forecasters. The uncertainties about past and future economic growth will not be resolved quickly. This is, of course, a guarantee that the lively economic debate now unfolding will continue for the foreseeable future.

The first priority for empirical research must be constant-quality price indexes for a wider variety of high-tech assets. These assets are becoming increasingly important in the U.S. economy, but only a small portion have constant-quality price deflators that translate the improved production characteristics into accurate measures of investment and output. This echoes the earlier findings of Gordon (1990), who reported that official price measures substantially overstate price changes for capital goods. In fact, Gordon identified computers and communications equipment as two assets with the largest overstatements, together with aircraft, which we have not included.[57] Much remains to be done to complete Gordon's program of implementing constant-quality price deflators for all components of investment in NIPA.

The second priority for research is to decompose the sources of economic growth to the industry level. Fortunately, the required methodology required is well established and increasingly familiar. Domar aggregation over industries underlies back-of-the-envelope calculations of the contribution of information technology to economic growth in Section III, as well as the more careful and comprehensive view of the contributions of industry-level productivity that we have presented in Section IV. This view will require considerable refinement to discriminate among alternative perspectives on the rapidly unfolding information economy. However, the evidence already available is informative on

[57]Gordon (1990), Table 12.3, p. 539.

the most important issue. This is the "new economy" view that the impact of information technology is like phlogiston, an invisible substance that spills over into every kind of economic activity and reveals its presence by increases in industry-level productivity growth across the U.S. economy. This view is simply inconsistent with the empirical evidence.

Our results suggest that while technology is clearly the driving force in the growth resurgence, familiar economic principles can be applied. Productivity growth in the production of information technology is responsible for a sizable part of the recent spurt in TFP growth and can be identified with price declines in high-tech assets and semiconductors. This has induced an eruption of investment in these assets that is responsible for capital deepening in the industries that use information technology. Information technology provides a dramatic illustration of economic incentives at work! However, there is no corresponding eruption of industry-level productivity growth in these sectors that would herald the arrival of phlogiston-like spillovers from production in the information technology sectors.

Many of the goods and services produced using high-tech capital may not be adequately measured, as suggested in the already classic paper of Griliches (1994). This may help to explain the surprisingly low productivity growth in many of the high-tech intensive, service industries. If the official data are understating both real investment in high-tech assets and the real consumption of commodities produced from these assets, the under-estimation of U.S. economic performance may be far more serious than we have suggested. Only as the statistical agencies continue their slow progress towards improved data and implementation of state-of-the-art methodology will this murky picture become more transparent.

Appendix A. Estimating Output

We begin with the National Income and Product Accounts (NIPA) as our primary source data. These data correspond to the most recent benchmark revision published by the Bureau of Economic Analysis (BEA) on October 29, 1999. These data provide measures of investment and consumption, in both current and chained 1996 dollars. The framework developed by Christensen and Jorgenson (1973), however, calls for a somewhat broader treatment of output than in the national accounts. Most important, consumers' durable goods are treated symmetrically with investment goods, since both are long-lived assets that are accumulated and provide a flow of services over their lifetimes. We use a rental price to impute a flow of consumers' durables services included in both

consumption output and capital input. We also employ a rental price to make relatively small imputations for the service flows from owner-occupied housing and institutional equipment.

Table A-1 presents the time series of total output in current dollars and the corresponding price index from 1959-98. The table also includes the current dollar value and price index for information technology output components—computer investment, software investment, communications investments, computer and software consumption, and the imputed service flow of computer and software consumer durables—as described in Equation (4) in the text.

Appendix B. Estimating Capital Services

Capital Services Methodology

We begin with some notation for measures of investment, capital stock, and capital services, for both individual assets and aggregates. For individual assets:

$I_{i,t}$ = quantity of investment in asset i at time t

$P_{i,,t}$ = price of investment in asset i at time t

d_i = geometric depreciation rate for asset i

$S_{i,t}$ = quantity of capital stock of asset i at time t

$P_{i,t}$ = price of capital stock of asset i at time t

$K_{i,t}$ = quantity of capital services from asset i at time t

$c_{i,t}$ = price of capital services from asset i at time t

where the i subscript refers to different types of tangible assets—equipment and structures, as well as consumers' durable assets, inventories, and land, all for time period t.

For economy-wide aggregates:

I_t = quantity index of aggregate investment at time t

$P_{I,t}$ = price index of aggregate investment at time t

S_t = quantity index of aggregate capital stock at time t

$P_{S,t}$ = price index of aggregate capital stock at time t

K_t = quantity index of aggregate capital services at time t

c_t = price of capital services at time t

$q_{K,t}$ = quality index of aggregate capital services at time t

Our starting point is investment in individual assets we assume that the price index for each asset measures investment goods in identically productive "efficiency units" over time. For example, the constant-quality price deflators in the NIPA measure the large increase in computing power as a decline in price of computers.[58] Thus, a faster computer is represented by more $I_{i,t}$ in a given period and a larger accumulation of $S_{i,t}$, as measured by the perpetual inventory equation:

$$S_{i,t} = S_{i,t-1}(1-\delta_i) + I_{i,t} = \sum_{\tau=0} (1-\delta_i)^{\tau} I_{i,t-\tau} \tag{B-1}$$

where capital is assumed to depreciate geometrically at the rate δ_i.

Equation (B-1) has the familiar interpretation that the capital stock is the weighted sum of past investments, where weights are derived from the relative efficiency profile of capital of different ages. Moreover, since Si,t is measured in base-year efficiency units, the appropriate price for valuing the capital stock is simply the investment price deflator, Pi,t.. Furthermore, Si,t represents the installed stock of capital, but we are interested in Ki,t, the flow of capital services from that stock over a given period. This distinction is not critical at the level of individual assets, but becomes important when we aggregate heterogeneous assets. For individual assets, we assume the flow of capital services is proportional to the average of the stock available at the end of the current and prior periods:

$$K_{i,t} = q_i \frac{(S_{i,t} + S_{i,t-1})}{2} \tag{B-2}$$

where q_i denotes this constant of proportionality, set equal to unity. Note that this differs from our earlier work, e.g., Jorgenson (1990), Jorgenson and Stiroh (1999), and Ho, Jorgenson, and Stiroh (1999), where capital service flows were assumed proportional to the lagged stock for individual assets.

Our approach assumes any improvement in input characteristics, such as a faster processor in a computer, is incorporated into investment $I_{i,t}$ via deflation of the nominal investment series. That is, investment deflators transform recent vintages of assets into an equivalent number of efficiency units of earlier vintages. This is consistent with the perfect substitutability assumption across

[58]See BLS (1997), particularly Chapter 14, for details on the quality adjustments incorporated into the producer prices indexes that are used as the primary deflators for the capital stock study. Cole et al. (1986) and Triplett (1986, 1989) provide details on the estimation of hedonic regressions for computers.

vintages and our use of the perpetual inventory method, where vintages differ in productive characteristics due to the age-related depreciation term.

We estimate a price of capital services that corresponds to the quantity flow of capital services via a rental price formula. In equilibrium, an investor is indifferent between two alternatives: earning a nominal rate of return, it, on a different investment or buying a unit of capital, collecting a rental fee, and then selling the depreciated asset in the next period. The equilibrium condition, therefore, is:

$$(1+i_t)P_{i,t-1} = c_{i,t} + (1-\delta_i)P_{i,t} \tag{B-3}$$

and rearranging yields a variation of the familiar cost of capital equation:

$$c_{i,t} = (i_t - \pi_{i,t})P_{i,t-1} + \delta_i P_{i,t} \tag{B-4}$$

where the asset-specific capital gains term is $\pi_{i,t} = (P_{i,t} - P_{i,t-1}) / P_{i,t-1}$.

This formulation of the cost of capital effectively includes asset-specific revaluation terms. If an investor expects capital gains on his investment, he will be willing to accept a lower service price. Conversely, investors require high service prices for assets like computers with large capital losses. Empirically, asset-specific revaluation terms can be problematic due to wide fluctuations in prices from period to period that can result in negative rental prices. However, asset-specific revaluation terms are becoming increasingly important as prices continue to decline for high-tech assets. Jorgenson and Stiroh (1999), for example, incorporated economy-wide asset revaluation terms for all assets and estimated a relatively modest growth contribution from computers.

As discussed by Jorgenson and Yun (1991), tax considerations also play an important role in rental prices. Following Jorgenson and Yun, we account for investment tax credits, capital consumption allowances, the statutory tax rate, property taxes, debt/equity financing, and personal taxes, by estimating an asset-specific, after-tax real rate of return, ri,t, that enters the cost of capital formula:

$$c_{i,t} = \frac{1 - ITC_{i,t} - \tau_t Z_{i,t}}{1-\tau_t}\left[r_{i,t} P_{i,t-1} + \delta_i P_{i,t}\right] + \tau_p P_{i,t-1} \tag{B-5}$$

where ITCi,t is the investment tax credit, tt is the statutory tax rate, Zi,t is the capital consumption allowance, tp is a property tax rate, all for asset i at time t, and ri,t is calculated as:

$$r_{i,t} = \beta[(1-\tau_t)i_t - \pi_{i,t}] + (1-\beta)\left[\frac{\rho_t - \pi_{i,t}(1-t_q^g)}{(1-t_q^e)\alpha + (1-t_q^g)(1-\alpha)}\right] \quad \text{(B-6)}$$

where β is the debt/capital ratio, it is the interest cost of debt, ρ_t is the rate of return to equity, α is the dividend payout ratio, and t_q^g and t_q^e are the tax rates on capital gains and dividends, respectively. $\pi_{i,t}$ is the inflation rate for asset i, which allows ri,t to vary across assets.[59]

Equations (B-1) through (B-6) describe the estimation of the price and quantity of capital services for individual assets: Pi,t and I i,t for investment; Pi,t and Si,t for capital stock; and ci,t and Ki,t for capital services. For an aggregate production function analysis, we require an aggregate measure of capital services, $K_t = f(K_{1,t}, K_{2,t}, ...K_{n,t})$, where n includes all types of reproducible fixed assets, consumers' durable assets, inventories, and land. We employ quantity indexes of to generate aggregate capital services, capital stock, and investment series.[60]

The growth rate of aggregate capital services is defined as a share-weighted average of the growth rate of the components:

$$\Delta \ln K_t = \sum_i \bar{v}_{i,t} \Delta \ln K_{i,t} \quad \text{(B-7)}$$

where weights are value shares of capital income:

$$\bar{v}_{i,t} = \frac{1}{2}\left(\frac{c_{i,t}K_{i,t}}{\sum_i c_{i,t}K_{i,t}} + \frac{c_{i,t-1}K_{i,t-1}}{\sum_i c_{i,t-1}K_{i,t-1}}\right) \quad \text{(B-8)}$$

and the price index of aggregate capital services is defined as:

$$c_t = \frac{\sum_i c_{i,t}K_{i,t}}{K_t} \quad \text{(B-9)}$$

Similarly, the quantity index of capital stock is given by:

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[59] A complication, of course, is that ρ_t is endogenous. We assume the after-tax rate of return to all assets is the same and estimate ρ_t as the return that exhausts the payment of capital across all assets in the corporate sector. In addition, tax considerations vary across ownership classes, e.g., corporate, non-corporate, and household. We account for these differences in our empirical work, but do not go into details here. See Jorgenson and Yun (1991, Chapter 2).

[60] See Diewert (1980) and Fisher (1992) for details.

$$\Delta \ln S_t = \sum_i \overline{w}_{i,t} \Delta \ln S_{i,t} \tag{B-10}$$

where the weights are now value shares of the aggregate capital stock:

$$\overline{w}_{i,t} = \frac{1}{2}\left(\frac{P_{i,t} S_{i,t}}{\sum_i P_{i,t} S_{i,t}} + \frac{P_{i,t-1} S_{i,t-1}}{\sum_i P_{i,t-1} S_{i,t-1}} \right) \tag{B-11}$$

and the price index for the aggregate capital stock index is:

$$P_{S,t} = \frac{\sum_i P_{i,t} S_{i,t}}{S_t} \tag{B-12}$$

Finally, the aggregate quantity index of investment is given by:

$$\Delta \ln I_t = \sum_i \overline{u}_{i,t} \Delta \ln I_{i,t} \tag{B-13}$$

where the weights are now value shares of aggregate investment:

$$\overline{u}_{i,t} = \frac{1}{2}\left(\frac{P_{i,t} I_{i,t}}{\sum_i P_{i,t} I_{i,t}} + \frac{P_{i,t-1} I_{i,t-1}}{\sum_i P_{i,t-1} I_{i,t-1}} \right) \tag{B-14}$$

and the price index for the aggregate investment index is:

$$P_{I,t} = \frac{\sum_i P_{i,t} I_{i,t}}{I_t} \tag{B-15}$$

The most important point from this derivation is the difference between the growth rate of aggregate capital services, Equation (B-7), and the growth rate of capital stock, Equation (B-10); this reflects two factors. First, the weights are different. The index of aggregate capital services uses rental prices as weights, while the index of aggregate capital stock uses investment prices. Assets with rapidly falling asset prices will have relatively large rental prices. Second, as can be seen from Equation (B-2), capital services are proportional to a two-period average stock, so the timing of capital services growth and capital stock growth differ for individual assets. In steady-state with a fixed capital to output ratio,

this distinction is not significant, but if asset accumulation is either accelerating or decelerating, this timing matters.

A second point to emphasize is that we can define an "aggregate index of capital quality," qK,t, analogously to Equation (B-2). We define the aggregate index of capital quality as qK,t=Kt/((St+St-1)/2), and it follows that the growth of capital quality is defined as:

(B-16)

$$\Delta \ln q_{K,t} = \Delta \ln K_t - \Delta \ln\left(\frac{(S_t + S_{t-1})}{2}\right) = \sum_i (\overline{v}_{i,t} - \overline{w}_{i,t}) \Delta \ln\left(\frac{(S_{t,i} + S_{t-1,i})}{2}\right)$$

Equation (B-16) defines growth in capital quality as the difference between the growth in capital services and the growth in average capital stock. This difference reflects substitution towards assets with relatively high rental price weights and high marginal products. For example, the rental price for computers is declining rapidly as prices fall, which induces substitution towards computers and rapid capital accumulation. However, the large depreciation rate and large negative revaluation term imply that computers have a high marginal product, so their rental price weight greatly exceeds their asset price weight. Substitution towards assets with higher marginal products is captured by our index of capital quality.

Investment and Capital Data

Our primary data source for estimating aggregating the flow of capital services is the "Investment Estimates of Fixed Reproducible Tangible Wealth, 1925-1997" (BEA (1998b, 1998c)). These data contain historical cost investment and chain-type quantity indices for 47 types of non-residential assets, 5 types of residential assets, and 13 different types of consumers' durable assets from 1925 to 1997. Table B-1 shows our reclassification of the BEA data into 52 non-residential assets, 5 residential assets, and 13 consumers' durable assets.[61]

Table B-2 presents the value and price index of the broadly defined capital stock, as well as individual information technology assets. Table B-3 presents similar data, but for capital service flows rather than capital stocks.[62] The price of capital

[61]Katz and Herman (1997) and Fraumeni (1997) provide details on the BEA methodology and underlying data sources.

[62]Note that these price indices have been normalized to equal 1.0 in 1996, so they do not correspond to the components of the capital service formula in Equation (B-5).

stocks for individual assets in Table B-2 is the same as the investment price in Table A-1, but the prices differ for aggregates due to differences between weights based on investment flows and those based on asset stocks. The price index for investment grows more slowly than the price index for assets, since short-lived assets with substantial relative price declines are a greater proportion of investment.

An important caveat about the underlying the investment data is that it runs only through 1997 and is not consistent with the BEA benchmark revision in October 1999. We have made several adjustments to reflect the BEA revision, make the data consistent with our earlier work, and extend the investment series to 1998. First, we have replaced the Tangible Wealth series on "computers and peripherals equipment" and replaced it with the NIPA investment series for "computers and peripherals equipment," in both current and chained 1996 dollars. These series were identical in the early years and differed by about 5% in current dollars in 1997. Similarly, we used the new NIPA series for investment in "software," "communications equipment," and for personal consumption of "computers, peripherals, and software" in both current and chained 1996 dollars. These NIPA series enable us to maintain a complete and consistent time series that incorporates the latest benchmark revisions and the expanded output concept that includes software.

Second, we have combined investment in residential equipment with "other equipment," a form of non-residential equipment. This does not change the investment or capital stock totals, but reallocates some investment and capital from the residential to the non-residential category.

Third, we control the total value of investment in major categories—structures, equipment and software, residential structures, and total consumers' durables—to correspond with NIPA aggregates. This adjustment maintains a consistent accounting for investment and purchases of consumers' durables as inputs and outputs. Computer investment, software investment, communications investment, and consumption of computers, peripherals, and software series not adjusted.

Fourth, we extended the investment series through 1998 based on NIPA estimates. For example, the 1998 growth rate for other fabricated metal products, steam engines, internal combustion engines, metalworking machinery, special industry machinery, general industrial equipment, and electrical transmission and distribution equipment were taken from the "other" equipment category in NIPA. The growth rate of each type of consumers' durables was taken directly from NIPA.

These procedures generated a complete time series of investment in 57 private assets (29 types of equipment and software, 23 types of non-residential structures, and 5 types of residential structures) and consumption of 13 consumers' durable assets in both current dollars and chained-1996 dollars from 1925 to 1998. For each asset, we created a real investment series by linking the historical cost investment and the quantity index in the base-year 1996. Capital stocks were then estimated using the perpetual inventory method in Equation (B-1) and a geometric depreciation rate, based on Fraumeni (1997) and reported in Table B-1.

Important exceptions are the depreciation rates for computers, software, and autos. BEA (1998a) reports that computer depreciation is based on the work of Oliner (1993, 1994), is non-geometric, and varies over time. We estimated a best-geometric approximation to the latest depreciation profile for different types of computer assets and used an average geometric depreciation rate of 0.315, which we used for computer investment, software investment, and consumption of computers, peripherals, and software. Similarly, we estimated a best geometric approximation to the depreciation profile for autos of 0.272.

We also assembled data on investment and land to complete our capital estimates. The inventory data come primarily from NIPA in the form of farm and non-farm inventories. Inventories are assumed to have a depreciation rate of zero and do not face an investment tax credit or capital consumption allowance, so the rental price formula is a simplified version of Equation (B-5).

Data on land are somewhat more problematic. Through 1995, the Federal Reserve Board published detailed data on land values and quantities in its "Balance Sheets for the U.S. Economy" study (Federal Reserve Board (1995, 1997)), but the underlying data became unreliable and are no longer published. We use the limited land data available in the "Flow of Funds Accounts of the United States" and historical data described in Jorgenson (1990) to estimate a price and a quantity of private land. As a practical matter, this quantity series varies very little, so its major impact is to slow the growth of capital by assigning a positive weight to the zero growth rate of land. Like inventories, depreciation, the investment tax credit, and capital consumption allowances for land are zero.

A final methodological detail involves negative service prices that sometimes result from the use of asset-specific revaluation terms. As can be seen from the simplified cost of capital formula in Equation (B-5), an estimated service price can be negative if asset inflation is high relative to the interest and depreciation rates. Economically, this is possible, implying capital gains were higher than expected. Negative service prices make aggregation difficult so we made

adjustments for several assets. In a small number of cases for reproducible assets and inventories, primarily structures in the 1970s, we used smoothed inflation for surrounding years rather than the current inflation in the cost of capital calculation. For land, which showed large capital gains throughout and has no depreciation, we used the economy-wide rate of asset inflation for all years.

Appendix C. Estimating Labor Input

Labor Input Methodology

We again begin with some notation for measures of hours worked, labor inputs, and labor quality for worker categories:

$H_{j,t}$ = quantity of hours worked by worker category j at time t

$w_{j,t}$ = price of an hour worked by worker category j at time t

$L_{j,t}$ = quantity of labor services from worker category j at time t

and for economy-wide aggregates:

H_t = quantity of aggregate hours worked at time t

W_t = average wage of hours worked at time t

L_t = quantity index of labor input at time t

$P_{L,t}$ = price index of labor input at time t

$q_{L,t}$ = quality index of labor input at time t

In general, the methodology for estimating labor input parallels capital services, but the lack of an investment-type variable makes the labor input somewhat more straightforward. For each individual category of workers, we begin by assuming the flow of labor service is proportional to hours worked:

(C-1) $$L_{j,t} = q_{L,j} H_{j,t}$$

where $q_{L,j}$ is the constant of proportionality for worker category j, set equal to unity.

The growth rate of aggregate labor input is defined as the share-weighted aggregate of the components as:

(C-2) $$\Delta \ln L_t = \sum_j \bar{v}_{j,t} \Delta \ln L_{j,t}$$

where weights are value shares of labor income:

(C-3)
$$\bar{v}_{j,t} = \frac{1}{2}\left(\frac{w_{j,t}L_{j,t}}{\sum_j w_{j,t}L_{j,t}} + \frac{w_{j,t-1}L_{j,t-1}}{\sum_j w_{j,t-1}L_{j,t-1}}\right)$$

and the price of aggregate labor input is defined as:

(C-4)
$$P_{L,t} = \frac{\sum_j w_{j,t}L_{j,t}}{L_t}$$

We define the "aggregate index of labor quality", qL,t, qL,t=Lt/Ht, where Ht is the unweighted sum of labor hours:

(C-5)
$$H_t = \sum_j H_{j,t}$$

The growth in labor quality is then defined as:

(C-6)
$$\Delta \ln q_{L,t} = \sum_j \bar{v}_{j,t}\Delta \ln H_{j,t} - \Delta \ln H_t$$

Equation (C-6) defines growth in labor quality as the difference between weighted and unweighted growth in labor hours. As with capital, this reflects substitutions among heterogeneous types of labor with different characteristics and different marginal products. As described by Ho and Jorgenson (1999), one can further decompose labor quality into components associated with different characteristics of labor, such as age, sex, and education.

Labor Data

Our primary data sources are individual observations from the decennial Censuses of Population for 1970, 1980, and 1990, the NIPA, and the annual Current Population Survey (CPS). The NIPA provide totals for hours worked and the Census and CPS allows us to estimate labor quality growth. Details on the construction of the labor data are in Ho and Jorgenson (1999). Table C-1 reports the primary labor used in this study, including the price, quantity, value, and quality of labor input, as well as employment, weekly hours, hourly compensation, and hours worked.

Briefly, the Censuses of Population provide detailed data on employment, hours, and labor compensation across demographic groups in census years. The CPS

data are used to interpolate similar data for intervening years and the NIPA data provide control totals. The demographic groups include 168 different types of workers, cross-classified by sex (male, female), class (employee, self-employed or unpaid), age (16-17, 18-24, 25-34, 45-54, 55-64,65+), and education (0-8 years grade school, 1-3 years high school, 4 years high school, 1-3 years college, 4 years college, 5+ years college).[63] Adjustments to the data include allocations of multiple job-holders, an estimation procedure to recover "top-coded" income data, and bridging to maintain consistent definitions of demographic groups over time.

These detailed data cover 1959 to 1995 and are taken from Ho and Jorgenson (1999). This allows us to estimate the quality of labor input for the private business sector, general government, and government enterprises, where only the private business sector index is used in the aggregate growth accounting results. For the years 1996-98, we estimate labor quality growth by holding relative wages across labor types constant, and incorporating demographic projections for the labor force. Hours worked by employees are taken from the latest data in the NIPA; hours worked by the self-employed are estimated by Ho and Jorgenson (1999).

Appendix D. Estimating Industry-Level Productivity

Our primary data are annual time series of inter-industry transactions in current and constant prices, including final demands by commodity, investment and labor inputs by industry, and output by industry. The first building block is a set of inter-industry transactions produced by the Employment Projections Office at the Bureau of Labor Statistics (BLS). These data report intermediate inputs and total value-added (the sum of capital and labor inputs and taxes) for 185 industries from 1977 to 1995. A major advantage of this BLS inter-industry data is that they provide the necessary interpolations between benchmark years.

We aggregate the data from the "Make" and "Use" tables to generate inter-industry transactions for 35 private business industries at approximately the two-digit Standard Industrial Classification (SIC) level. These tables enable us to generate growth rates of industry outputs, growth rates of intermediate inputs, and shares of intermediate inputs as needed in Equation (29). They also provide control totals for value-added in each industry, the sum of the values of capital and labor services and taxes.

[63]There is also an industry dimension, which we do not exploit in this aggregate framework, but is used in the industry productivity analysis discussed below.

Estimation of capital services and labor input follows the procedures described above for each industry. We collected information from three sources to estimate prices and quantities of capital and labor inputs by industry. An industry-level breakdown of the value of capital and labor input is available in the "gross product originating" series described in Lum and Yuskavage (1997) of the BEA. Investments by asset classes and industries are from the BEA Tangible Wealth Survey (BEA (1998a), described by Katz and Herman (1997)). Labor data across industries are from the decennial Census of Population and the annual Current Population Survey. We use employ the prices and quantities of labor services for each industry constructed by Ho and Jorgenson (1999).

We also generate capital and labor services for a Private Household sector and the Government sector.[64] For Private Households, the value of labor services equals labor income in BLS's private household industry, while capital income reflects the imputed flow of capital services from residential housing, consumers' durables, and household land as described above. For Government, labor income equals labor compensation of general government employees and capital income is an estimate flow of capital services from government capital.[65] Note Government Enterprises are treated as a private business industry and are separate from the General Government.

Appendix E. Extrapolation for 1999

Table 2 presents primary growth accounting results through 1998 and preliminary estimates for 1999. The data through 1998 are based on the detailed methodology described in Appendixes A-D; the 1999 data are extrapolated based on currently available data and recent trends.

Our approach for extrapolating growth accounting results through 1999 was to estimate 1999 shares and growth rates for major categories like labor, capital, and information technology components, as well as the growth in output. The 1999 labor share was estimated from 1995-98 data, hours growth are from BLS (2000), and labor quality growth came from the projections described above. The 1999 growth rates of information technology outputs were taken from the NIPA, and shares were estimated from 1995-98 data. The 1999 growth rates of information

[64] The Private Household and Government sectors include only capital and labor as inputs. Output in these sectors is defined via a Tornqvist index of capital and labor inputs, so productivity growth is zero by definition.

[65] BEA includes a similar imputation for the flow of government capital services in the national accounts, but our methodology includes a return to capital, as well as depreciation as estimated by BEA.

technology inputs were estimated from recent investment data and the perpetual inventory method, and shares were estimated from 1995-98 data. The 1999 growth of other capital were estimates from NIPA investment data for broad categories like equipment and software, non-residential structures, residential structures, as well as consumers' durable purchases; the income share was calculated from the estimated labor share. Output growth was estimated from growth in BLS business output and BEA GDP, with adjustment made for different output concepts. Finally, TFP growth for 1999 was estimated as the difference in the estimated output growth and share-weighted input growth.

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Figures and Tables

Table 1

Average Growth Rates of Selected Outputs and Inputs (%)

	1990–95		1995–98	
	Price	Quant.	Price	Quant.
Outputs				
Private Domestic Output (Y)	1.70	2.74	1.37	4.73
Other (Yn)	2.01	2.25	2.02	3.82
Computer and Software Consumption (Cc)	−21.50	38.67	−36.93	49.26
Computer Investment (Ic)	−14.59	24.89	−27.58	38.08
Software Investment (Is)	−1.41	11.59	−2.16	15.18
Communications Investment (Im)	−1.50	6.17	−1.73	12.79
Computer and Software CD Services (Dc)	−19.34	34.79	−28.62	44.57
Inputs				
Total Capital Services (K)	0.60	2.83	2.54	4.80
Other (Kn)	1.00	1.78	4.20	2.91
Computer Capital (Kc)	−10.59	18.16	−20.09	34.10
Software Capital (Ks)	−2.07	13.22	−0.87	13.00
Communications Capital (Km)	3.10	4.31	−7.09	7.80
Total Consumption Services (D)	1.98	2.91	−0.67	5.39
Non–Computer and Software (Dn)	2.55	2.07	0.54	3.73
Computer and Software CD Services (Dc)	−19.34	34.79	−28.62	44.57
Labor(L)	2.92	2.01	2.80	2.81

NOTE: CD refers to consumers' durable assets.

Table 2

Growth in U.S. Private Domestic Output and the Sources of Growth, 1959-99 (%)

	1959–98	1959–73	1973–90	1990–95	1995–98	1995–99*
Growth in Private Domestic Output Growth (Y)	3.630	4.325	3.126	2.740	4.729	4.763
Contribution of Selected Output Components						
Other (Yn)	3.275	4.184	2.782	2.178	3.659	3.657
Computer and Software Consumption (Cc)	0.035	0.000	0.023	0.092	0.167	0.175
Computer In vestment (Ic)	0.150	0.067	0.162	0.200	0.385	0.388
Software In vestment (Is)	0.074	0.025	0.075	0.128	0.208	0.212
Communications Investment (Im)	0.060	0.048	0.061	0.053	0.122	0.128
Computer and Software C D Services (Dc)	0.036	0.000	0.023	0.089	0.187	0.204
Contribution of Capital Services (K)	1.260	1.436	1.157	0.908	1.611	1.727
Other (Kn)	0.936	1.261	0.807	0.509	0.857	0.923
Computers (Kc)	0.177	0.086	0.199	0.187	0.458	0.490
Software (Ks)	0.075	0.026	0.071	0.154	0.193	0.205
Communications (Km)	0.073	0.062	0.080	0.058	0.104	0.109
Contribution of CD Services (D)	0.510	0.632	0.465	0.292	0.558	0.608
Other (Dn)	0.474	0.632	0.442	0.202	0.370	0.403
Computers and Software (Dc)	0.036	0.000	0.023	0.089	0.187	0.204
Contribution of Labor (L)	1.233	1.249	1.174	1.182	1.572	1.438
Aggregate Total F actor Productivity (TFP)	0.628	1.009	0.330	0.358	0.987	0.991
Growth of Capital and CD Services	4.212	4.985	3.847	2.851	4.935	5.286
Growth of Lab or In put	2.130	2.141	2.035	2.014	2.810	2.575
Contribution of Capital and CD Quality	0.449	0.402	0.405	0.434	0.945	1.041
Contribution of Capital an d CD Stock	1.320	1.664	1.217	0.765	1.225	1.293
Contribution of Labor Quality	0.315	0.447	0.200	0.370	0.253	0.248
Contribution of Labor Hours	0.918	0.802	0.974	0.812	1.319	1.190
Average Labor Productivity (ALP)	2.042	2.948	1.437	1.366	2.371	2.580

*Preliminary

NOTES: A contribution of an output and an input is defined as the share-weighted, real growth rate. CD refers t o consumers' durable assets. 1995–99 results include preliminary estimates for 1999; see the appendix for details on estimation and data sources.

Table 3

The Sources of ALP Growth, 1959–98 (%)

Variable	1959–98	1959–73	1973–90	1990–95	1995–98
Growth of Private Domestic Output (Y)	3.630	4.325	3.126	2.740	4.729
Growth in Hours (H)	1.588	1.377	1.689	1.374	2.358
Growth in ALP (Y/H)	2.042	2.948	1.437	1.366	2.371
ALP Contribution of Capital Deepening	1.100	1.492	0.908	0.637	1.131
ALP Contribution of Labor Quality	0.315	0.447	0.200	0.370	0.253
ALP Contribution of TFP	0.628	1.009	0.330	0.358	0.987

NOTE: ALP Contributions are defined in Equation (3).

Table 4

Impact of Alternative Deflation of Software and Communications Equipment on the Sources of U.S. Economic Growth, 1959–98

	Base Case				Moderate Price Decline				Rapid Price Decline			
	1959–73	1973–90	1990–95	1995–98	1959–73	1973–90	1990–95	1995–98	1959–73	1973–90	1990–95	1995–98
Growth in Private Domestic Output Growth (Y)	4.33	3.13	2.74	4.73	4.35	3.30	2.90	4.89	4.36	3.38	3.03	5.07
Contribution of Selected Output Components												
Other (Yn)	4.18	2.78	2.18	3.66	4.12	2.76	2.17	3.66	4.08	2.75	2.16	3.66
Computer and Software Consumption (Cc)	0.00	0.02	0.09	0.17	0.00	0.02	0.09	0.17	0.00	0.02	0.09	0.17
Computer Investment (Ic)	0.07	0.16	0.20	0.39	0.07	0.16	0.20	0.39	0.07	0.16	0.20	0.39
Software Investment (Is)	0.03	0.08	0.13	0.21	0.04	0.14	0.22	0.29	0.05	0.17	0.29	0.40
Communications Investment (Im)	0.05	0.06	0.05	0.12	0.12	0.19	0.13	0.21	0.16	0.25	0.19	0.27
Computer and Software CD Services (Dc)	0.00	0.02	0.09	0.19	0.00	0.02	0.09	0.19	0.00	0.02	0.09	0.19
Contribution of Capital Services (K)	1.44	1.16	0.91	1.61	1.54	1.39	1.15	1.83	1.61	1.51	1.32	2.09
Other (n)	1.26	0.81	0.51	0.86	1.25	0.80	0.51	0.86	1.25	0.79	0.51	0.85
Computers (Kc)	0.09	0.20	0.19	0.46	0.09	0.20	0.19	0.46	0.09	0.20	0.19	0.46
Software (Ks)	0.03	0.07	0.15	0.19	0.05	0.15	0.28	0.29	0.06	0.18	0.36	0.45
Communications (Km)	0.06	0.08	0.06	0.10	0.16	0.25	0.18	0.23	0.22	0.34	0.27	0.33
Contribution of CD Services (D)	0.63	0.47	0.29	0.56	0.63	0.46	0.29	0.56	0.63	0.46	0.29	0.56
Non-Computers and Software (Dn)	0.63	0.44	0.20	0.37	0.63	0.44	0.20	0.37	0.63	0.44	0.20	0.37
Computers and Software (Dc)	0.00	0.02	0.09	0.19	0.00	0.02	0.09	0.19	0.00	0.02	0.09	0.19
Contribution of Labor (L)	1.25	1.17	1.18	1.57	1.25	1.17	1.18	1.57	1.25	1.18	1.18	1.57
Aggregate Total Factor Productivity (TFP)	1.01	0.33	0.36	0.99	0.94	0.27	0.27	0.93	0.88	0.22	0.23	0.85
Growth of Capital and CD Services	4.99	3.85	2.85	4.94	5.24	4.40	3.43	5.44	5.41	4.70	3.84	6.02

Table 4—Continued

	Base Case				Moderate Price Decline				Rapid Price Decline			
	1959–73	1973–90	1990–95	1995–98	1959–73	1973–90	1990–95	1995–98	1959–73	1973–90	1990–95	1995–98
Growth of Labor Input	2.14	2.04	2.01	2.81	2.14	2.04	2.01	2.81	2.14	2.04	2.01	2.81
Contribution of Capital and CD Quality	0.40	0.41	0.43	0.95	0.48	0.59	0.63	1.11	0.54	0.70	0.78	1.34
Contribution of Capital and CD Stock	1.66	1.22	0.77	1.23	1.68	1.26	0.82	1.28	1.69	1.27	0.84	1.31
Contribution of Labor Quality	0.45	0.20	0.37	0.25	0.45	0.20	0.37	0.25	0.45	0.20	0.37	0.25
Contribution of Labor Hours	0.80	0.97	0.81	1.32	0.80	0.97	0.81	1.32	0.80	0.98	0.81	1.32
Average Labor Productivity (ALP)	2.95	1.44	1.37	2.37	2.98	1.61	1.52	2.53	2.99	1.69	1.65	2.72

NOTES: Base Case uses official NIPA price data. Moderate Price Decline uses prepackaged software deflator for all software and annual price changes of –10.7% for communications equipment. Rapid Price Decline uses annual price changes of –16% for software and –17.9% for communications equipment. See text for details and sources. A contribution is defi ned as the share-weighted,realgrowthrate. CDrefers toconsumers'durableassets.

Table 5

Information Technology Decomposition of TFP Growth for Alternative Deflation Cases, 1990–98

	Base Case		Moderate Price Decline		Rapid Price Decline	
	1990–95	1995–98	1990–95	1995–98	1990–95	1995–98
Aggregate TFP Growth	0.36	0.99	0.27	0.93	0.23	0.85
			TFP Contribution			
Information Technology	0.25	0.44	0.46	0.64	0.64	0.86
Computers	0.16	0.32	0.16	0.32	0.16	0.32
Software	0.05	0.08	0.17	0.18	0.28	0.34
Communications	0.04	0.04	0.13	0.13	0.21	0.20
Non–Information Technology	0.11	0.55	–0.19	0.29	–0.41	–0.01
			Relative Price Change			
Computers	–16.6	–29.6	–16.6	–29.6	–16.6	–29.6
Software	–3.4	–4.2	–11.3	–9.7	–18.0	–18.0
Communications	–3.5	–3.8	–12.7	–12.7	–19.9	–19.9
			Average Nominal Share			
Computers	0.96	1.09	0.96	1.09	0.96	1.09
Software	1.54	1.88	1.54	1.88	1.54	1.88
Communications	1.05	1.02	1.05	1.02	1.05	1.02

NOTES: Base Case uses official NIPA price data. Moderate Price Decline uses prepackaged software deflator for all software and –10.7% for communications equipment. Rapid Price Decline uses –16% for software and –17.9% for communications equipment. See text for details and sources. A TFP contribution is defined as t he share-weighted, growth rate of relative prices.

Table 6

Growth Rates of Output, Inputs, and Total Factor Productivity Comparison of BLS, CBO, and Jorgenson-Stiroh

	BLS Nonfarm Business	CBO Overall Economy			CBO Nonfarm Business			Jorgenson-Stiroh	
	1990–1999	1980–90	1990–99	1999–2010	1980–90	1990–99	1999–2010	1980–90	1990–98
Real Output	3.74	3.0	2.9	3.1	3.2	3.4	3.5	3.48	3.55
Labor Input								2.14	2.34
Hours Worked	1.68	1.6	1.2	1.1	1.6	1.5	1.2	1.81	1.76
Labor Quality								0.33	0.58
Capital Input					3.6	3.6	4.4	3.57	3.68
TFP—not adjusted for labor quality					0.9	1.2	1.4	0.91	0.97
TFP—adjusted for labor quality								0.73	0.63
ALP	2.06	1.4	1.7	1.9	1.5	1.9	2.3	1.67	1.79

NOTE: CBO estimates refer to "potential" series that are adjusted for business cycle effects. Growth rates do not exactly match Table 5 since discrete growth rate are used here for consistency with CBO's methodology. Hours worked for CBO Overall Economy refers to potential labor force.

Table 7

1996 Value Added and Gross Output by Industry

Industry	SIC Codes	Value Added	Gross Output
Agriculture	01–02, 07–09	133.3	292.2
Metal Mining	10	8.8	10.7
Coal Mining	11–12	14.7	21.1
Petroleum and Gas	13	57.4	83.3
Nonmetallic Mining	14	10.5	17.0
Construction	15–17	336.0	685.5
Food Products	20	147.2	447.6
Tobacco Products	21	26.7	32.7
Textile Mill Products	22	19.9	58.9
Apparel and Textiles	23	40.7	98.5
Lumber and Wood	24	34.2	106.7
Furniture and Fixtures	25	23.4	54.5
Paper Products	26	68.3	161.0
Printing and Publishing	27	113.5	195.6
Chemical Products	28	184.0	371.2
Petroleum Refining	29	44.7	184.3
Rubber and Plastic	30	64.1	148.9
Leather Products	31	3.4	8.1
Stone, Clay, and Glass	32	40.4	79.1
Primary Metals	33	57.6	182.1
Fabricated Metals	34	98.4	208.8
Industrial Machinery and Equipment	35	177.8	370.5
Electronic and Electric Equipment	36	161.9	320.4
Motor Vehicles	371	84.9	341.6
Other Transportation Equipment	372–379	68.0	143.8
Instruments	38	81.3	150.0
Miscellaneous Manufacturing	39	24.8	49.3
Transport and Warehouse	40–47	258.6	487.7
Communications	48	189.7	315.8
Electric Utilities	491, %493	111.8	186.7
Gas Utilities	492, %493, 496	32.9	57.9
Trade	50–59	1,201.2	1,606.4
FIRE	60–67	857.8	1,405.1
Services	70–87, 494–495	1,551.9	2,542.8
Government Enterprises		95.2	220.2
Private Households	88	1,248.4	1,248.4
General Government		1,028.1	1,028.1

NOTE: All values are in current dollars. Value–added refers to payments to capital and labor; Gross output includes payments for intermediate inputs.

Table 8

Sources of U.S. Economic Growth by Industry, 1958–96

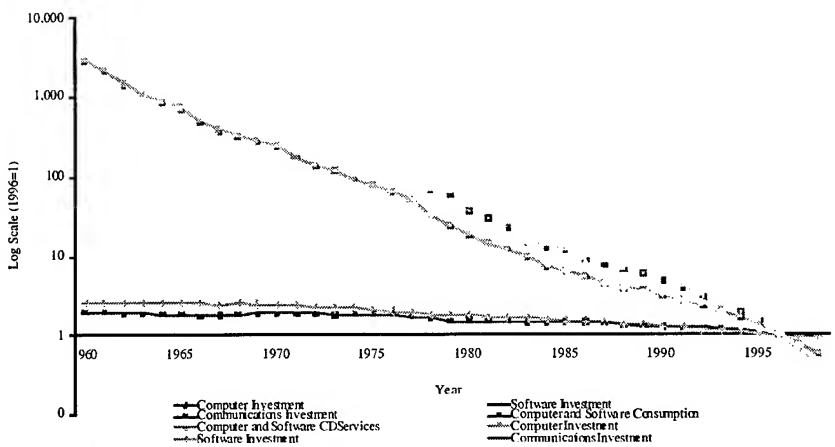
Industry	Output Growth	Contributions of Inputs: Capital	Labor	Energy	Materials	Productivity Growth	ALP Growth	Domar Weight
Agriculture	1.70	0.19	–0.13	–0.04	0.51	1.17	3.21	0.062
Metal Mining	0.78	0.73	–0.07	–0.07	–0.26	0.44	0.99	0.003
Coal Mining	2.35	0.82	0.00	0.06	0.63	0.84	2.32	0.005
Petroleum and Gas	0.43	0.61	–0.01	0.06	0.20	–0.44	0.88	0.022
Nonmetallic Mining	1.62	0.59	0.18	0.06	0.34	0.46	1.52	0.003
Construction	1.43	0.07	0.87	0.02	0.91	–0.44	–0.38	0.113
Food Products	2.20	0.21	0.18	0.00	1.27	0.54	1.59	0.076
Tobacco Products	0.43	0.59	0.05	0.00	–0.01	–0.20	0.88	0.004
Textile Mill Products	2.23	0.12	0.02	0.01	0.86	1.23	2.54	0.013
Apparel and Textiles	2.03	0.24	0.17	0.00	0.82	0.80	2.01	0.022
Lumber and Wood	2.24	0.21	0.33	0.02	1.70	–0.02	1.55	0.015
Furniture and Fixtures	2.91	0.31	0.58	0.02	1.44	0.56	1.78	0.007
Paper Products	2.89	0.50	0.40	0.05	1.51	0.42	1.96	0.022
Printing and Publishing	2.51	0.55	1.20	0.02	1.19	–0.44	0.14	0.024
Chemical Products	3.47	0.74	0.47	0.09	1.58	0.58	2.02	0.048
Petroleum Refining	2.21	0.44	0.24	0.49	0.71	0.33	0.80	0.033
Rubber and Plastic	5.17	0.47	1.16	0.08	2.43	1.04	1.94	0.016
Leather Products	–2.06	–0.11	–1.13	–0.02	–1.08	0.28	2.08	0.004
Stone, Clay, and Glass	1.86	0.26	0.37	0.00	0.82	0.41	1.30	0.014
Primary Metals	1.14	0.13	0.05	–0.03	0.77	0.22	1.51	0.040
Fabricated Metals	2.28	0.26	0.28	0.00	1.09	0.65	1.88	0.035
Industrial Machinery and Equipment	4.79	0.52	0.75	0.02	2.04	1.46	3.15	0.048

Table 8—Continued

		Contributions of Inputs						
Industry	Output Growth	Capital	Labor	Energy	Materials	Productivity Growth	ALP Growth	Domar Weight
Electronic and Electric Equipment	5.46	0.76	0.65	0.03	2.04	1.98	4.08	0.036
Motor Vehicles	3.61	0.28	0.29	0.02	2.78	0.24	2.28	0.043
Other Transportation Equipment	1.31	0.23	0.37	0.00	0.52	0.18	1.00	0.027
Instruments	5.23	0.65	1.44	0.03	1.99	1.12	2.57	0.017
Miscellaneous Manufacturing	2.53	0.34	0.41	0.00	0.95	0.82	2.08	0.008
Transport and Warehouse	3.25	0.20	0.72	0.12	1.34	0.86	1.74	0.061
Communications	5.00	1.62	0.53	0.02	1.95	0.88	3.93	0.033
Electric Utilities	3.22	1.01	0.20	0.67	0.83	0.51	2.52	0.026
Gas Utilities	0.56	0.66	–0.04	0.14	0.05	–0.24	0.94	0.016
Trade	3.66	0.62	0.83	0.04	1.19	0.98	2.49	0.195
FIRE	3.42	1.14	0.94	0.00	1.52	–0.18	0.66	0.131
Services	4.34	0.84	1.70	0.07	1.92	–0.19	0.92	0.208
Government Enterprises	2.86	1.24	1.08	0.23	0.83	–0.52	0.49	0.022
Private Households	3.50	3.55	–0.06	0.00	0.00	0.00	5.98	0.137
General Government	1.35	0.60	0.75	0.00	0.00	0.00	0.46	0.131

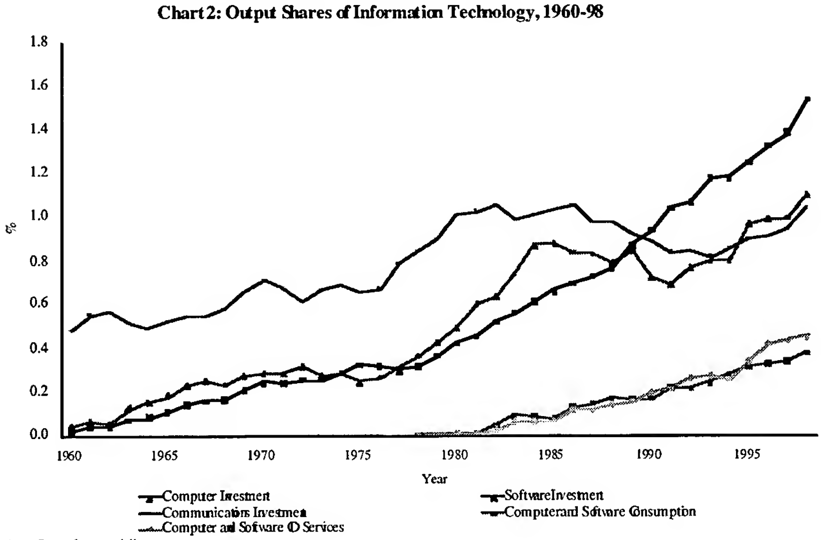
NOTES: Output Growth is the average annual growth i n real gross output. Contributions of Inputs are defined as the average, share–weighted growth of the input.. Productivity Growth is defined in Equation (8). ALP Growth is the growth in average labor productivity. Domar Weight is the average ratio of industry gross output to aggregate value added as defined in Equation (9). All numbers except Domar Weights are percentages.

Chart 1: Relative Prices of Information Technology Output, 1960-98



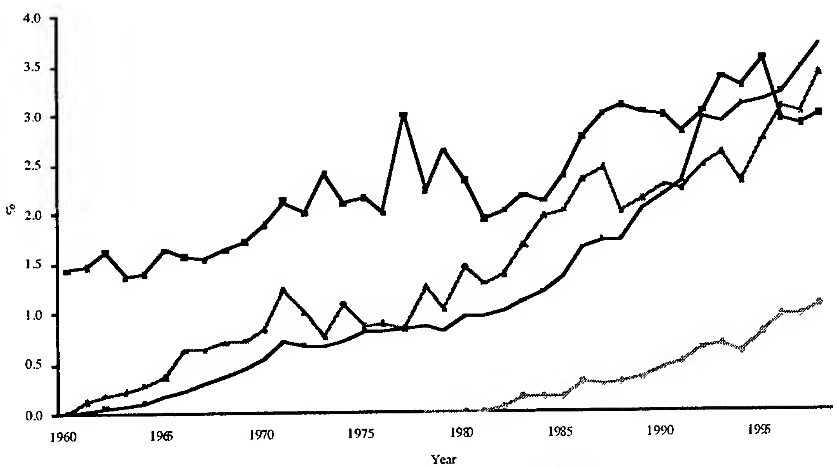
Notes: All price indexes are relative to the output price index.

Chart 2: Output Shares of Information Technology, 1960-98



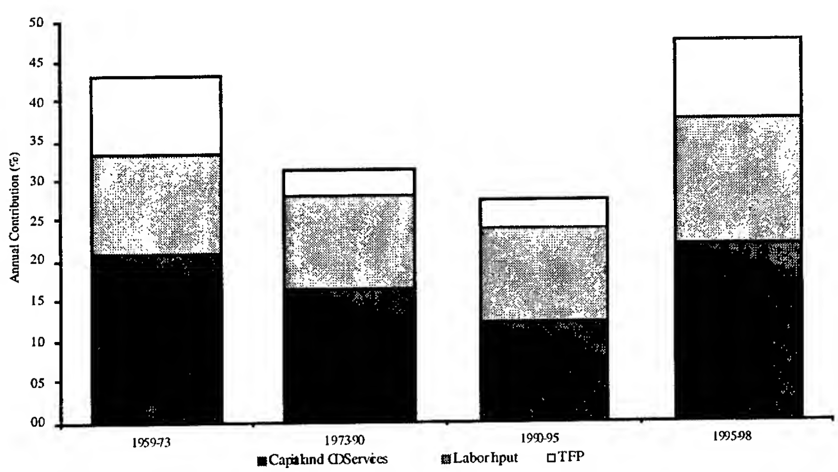
Notes: Share of current dollar output.

Chart 3: Input Shares of Information Technology, 1960-98



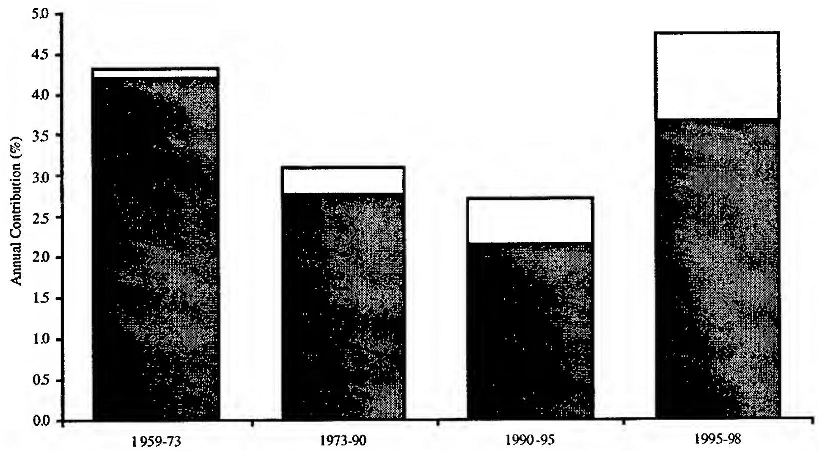
Notes: Share of current dollar capital and consumers' durable services

Chart 4: Sources of U.S. Economic Growth, 1959-98



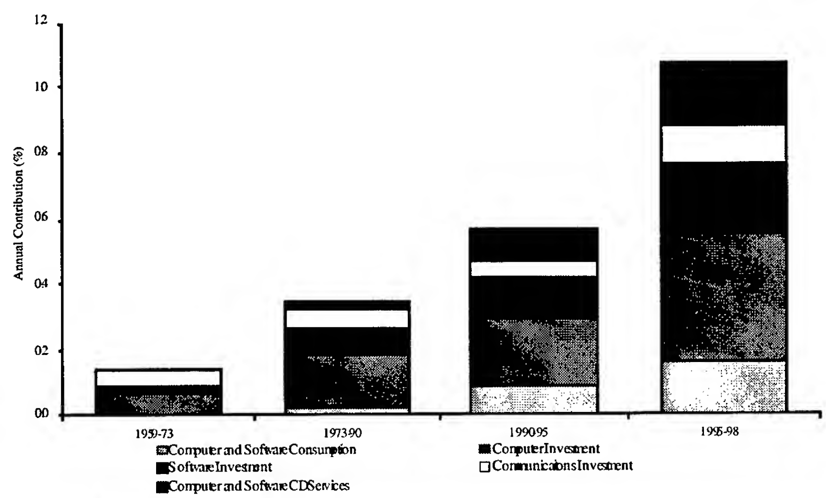
Notes: An input's contribution is the average share-weighted, annual growth rate. TFP defined in Equation (2) in text.

Chart 5: Output Contribution of Information Technology, 1959-98



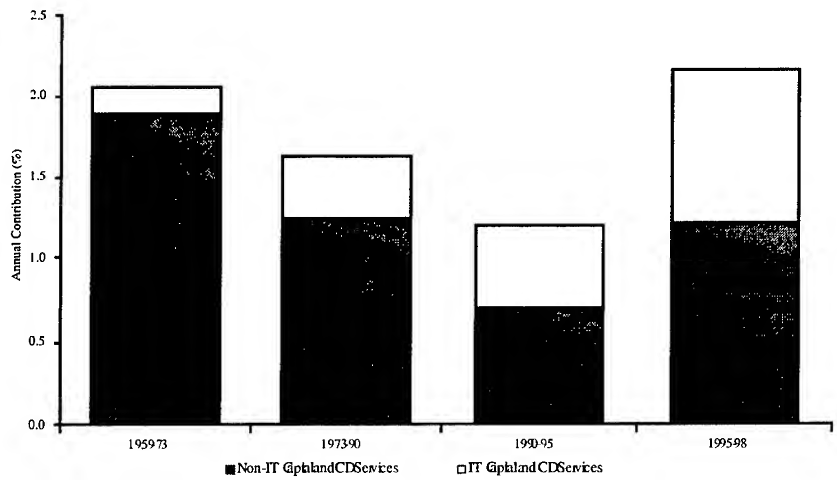
Notes: An output's contribution is the average share-weighted annual growth rate.

Chart 6: Output Contribution of Information Technology Assets, 1959-98



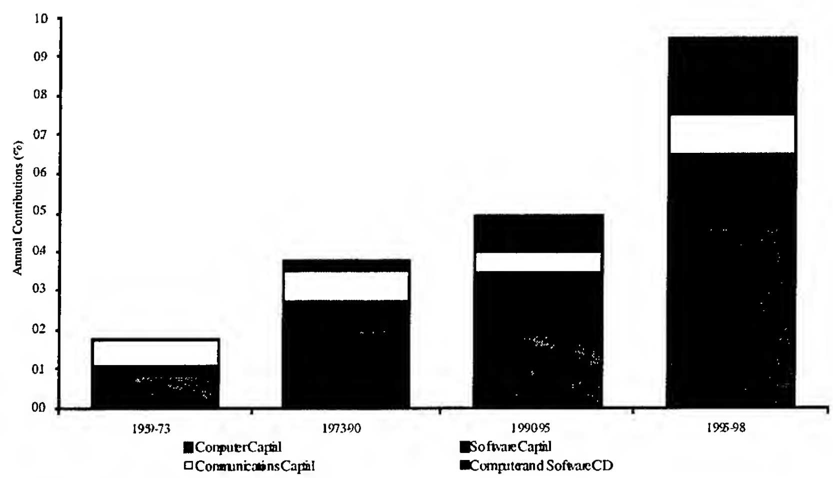
Notes: An output's contribution is the average share-weighted annual growth rate.

Chart 7: Input Contribution of Information Technology, 1959-98



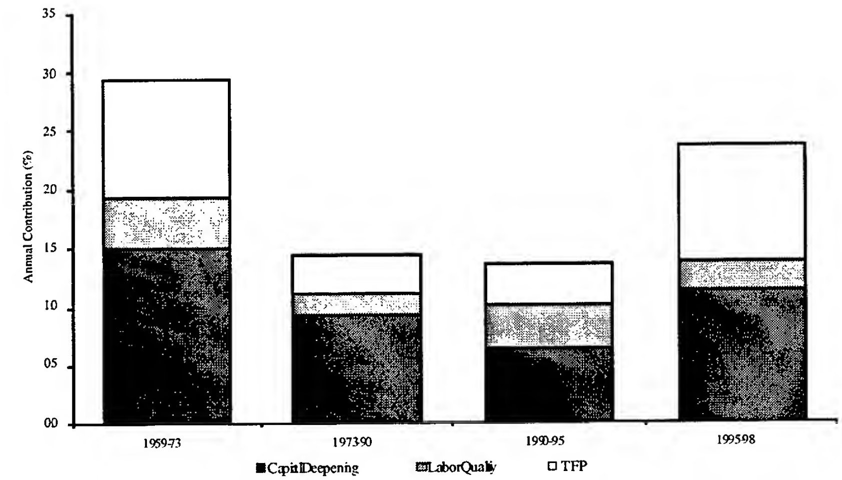
Notes: An input's contribution is the average share-weighted annual growth rate.

Chart 8: Input Contribution of Information Technology Assets, 1959-98



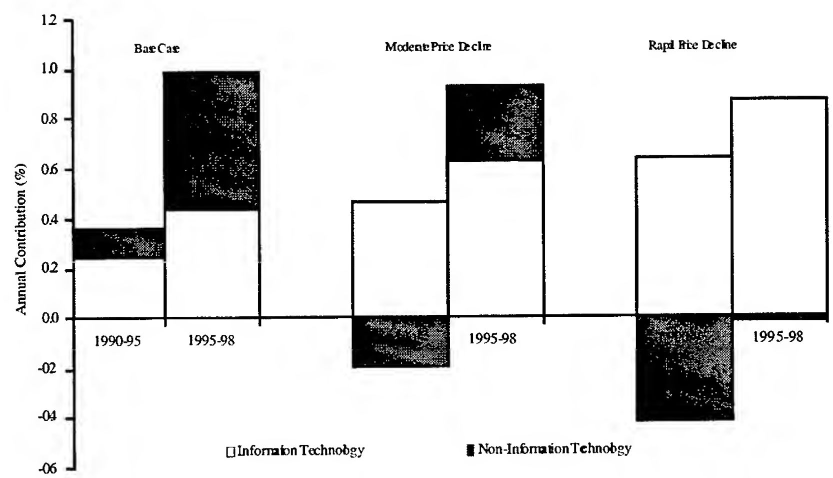
Notes: An input's contribution is the average share-weighted annual growth rate.

Chart 9: Sources of U.S. Labor Productivity Growth, 1959-98



Notes: Annual contributions are defined in Equation (3) in text.

Chart 10: TFP Decomposition for Alternative Deflation Cases



Notes: Annual contribution of information technology is the share-weighted decline in relative prices.

Chart 11: Industry Contributions to Aggregate Total Factor Productivity Growth, 1958-96

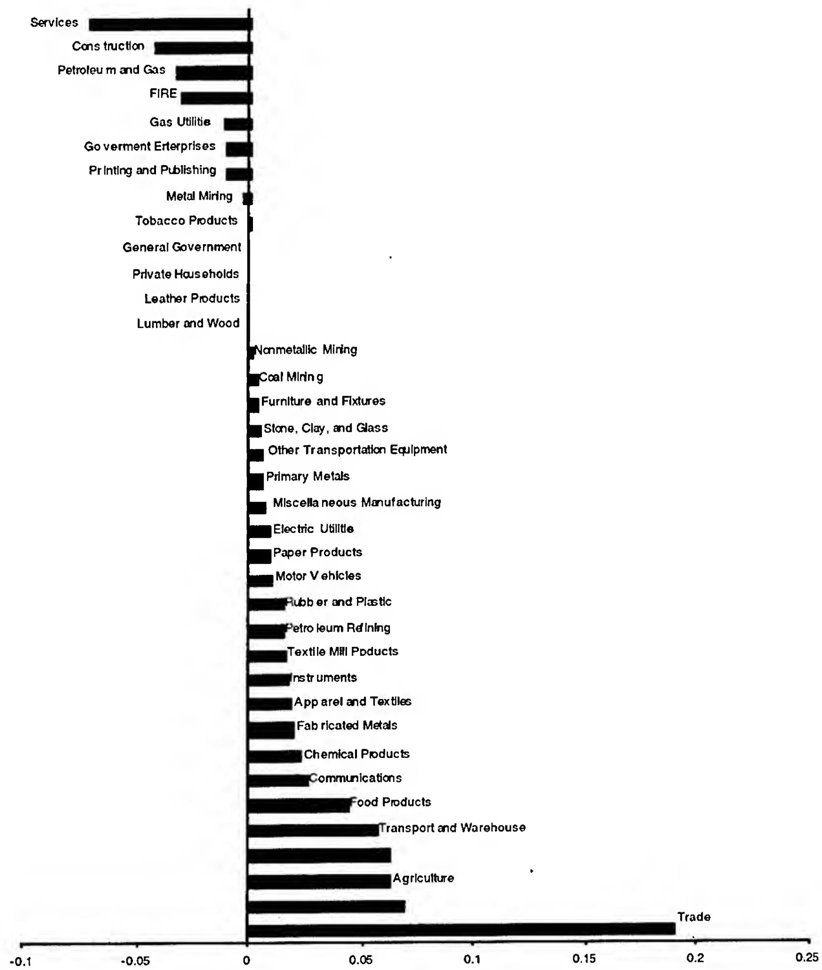


Table A-1

Private Domestic Output and High–Tech Assets

	Private Domestic Output		Computer Investment		Software Investment		Communications Investment		Computer & Software Investment		Computer & Software Consumption Services	
Year	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price
1959	484.1	0.25	0.00	0.00	0.00	0.00	1.80	0.47	0.00	0.00	0.00	0.00
1960	472.8	0.24	0.20	697.30	0.10	0.61	2.30	0.47	0.00	0.00	0.00	0.00
1961	490.1	0.24	0.30	522.97	0.20	0.62	2.70	0.47	0.00	0.00	0.00	0.00
1962	527.1	0.25	0.30	369.16	0.20	0.63	3.00	0.46	0.00	0.00	0.00	0.00
1963	562.1	0.25	0.70	276.29	0.40	0.63	2.90	0.46	0.00	0.00	0.00	0.00
1964	606.4	0.26	0.90	229.60	0.50	0.64	3.00	0.47	0.00	0.00	0.00	0.00
1965	664.2	0.26	1.20	188.74	0.70	0.65	3.50	0.47	0.00	0.00	0.00	0.00
1966	728.9	0.27	1.70	132.70	1.00	0.66	4.00	0.47	0.00	0.00	0.00	0.00
1967	763.1	0.28	1.90	107.71	1.20	0.67	4.20	0.49	0.00	0.00	0.00	0.00
1968	811.0	0.28	1.90	92.00	1.30	0.68	4.70	0.51	0.00	0.00	0.00	0.00
1969	877.7	0.29	2.40	83.26	1.80	0.70	5.80	0.54	0.00	0.00	0.00	0.00
1970	937.9	0.31	2.70	74.81	2.30	0.73	6.70	0.57	0.00	0.00	0.00	0.00
1971	991.5	0.32	2.80	56.98	2.40	0.73	6.80	0.60	0.00	0.00	0.00	0.00
1972	1,102.9	0.33	3.50	45.93	2.80	0.73	6.80	0.62	0.00	0.00	0.00	0.00
1973	1,255.0	0.36	3.50	43.53	3.20	0.75	8.40	0.64	0.00	0.00	0.00	0.00
1974	1,345.9	0.38	3.90	35.55	3.90	0.80	9.40	0.69	0.00	0.00	0.00	0.00
1975	1,472.7	0.42	3.60	32.89	4.80	0.85	9.70	0.76	0.00	0.00	0.00	0.00
1976	1,643.0	0.44	4.40	27.47	5.20	0.87	11.10	0.80	0.00	0.00	0.00	0.00
1977	1,828.1	0.47	5.70	23.90	5.50	0.89	14.40	0.78	0.00	0.00	0.00	0.00
1978	2,080.4	0.50	7.60	16.17	6.60	0.90	17.70	0.81	0.10	33.68	0.02	17.84
1979	2,377.8	0.56	10.20	13.40	8.70	0.95	21.40	0.83	0.10	32.81	0.07	19.01
1980	2,525.9	0.59	12.50	10.46	10.70	1.01	25.70	0.88	0.20	22.11	0.20	25.93
1981	2,825.6	0.65	17.10	9.19	12.90	1.07	29.00	0.96	0.40	18.79	0.25	13.90
1982	2,953.5	0.69	18.90	8.22	15.40	1.12	31.10	1.01	1.40	15.12	0.74	11.96

Table A-1—Continued

	Private Domestic Output		Computer Investment		Software Investment		Communications Investment		Computer & Software Investment		Computer & Software Consumption Services	
Year	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price
1983	3,207.7	0.72	23.90	6.86	18.00	1.13	31.90	1.03	2.90	10.71	2.07	10.39
1984	3,610.3	0.75	31.60	5.55	22.10	1.14	36.60	1.07	3.00	9.41	2.37	6.07
1985	3,844.1	0.76	33.70	4.72	25.60	1.13	39.90	1.09	2.90	8.68	2.70	4.93
1986	3,967.4	0.76	33.40	4.06	27.80	1.12	42.10	1.10	5.20	6.54	4.84	5.61
1987	4,310.8	0.79	35.80	3.46	31.40	1.12	42.10	1.10	6.20	5.91	4.91	3.54
1988	4,766.1	0.84	38.00	3.21	36.70	1.14	46.70	1.10	8.20	5.41	6.65	3.24
1989	5,070.5	0.86	43.10	3.00	44.40	1.11	46.90	1.10	8.30	5.02	7.89	2.85
1990	5,346.8	0.89	38.60	2.72	50.20	1.09	47.50	1.11	8.90	4.22	10.46	2.97
1991	5,427.2	0.91	37.70	2.45	56.60	1.10	45.70	1.11	11.90	3.53	11.66	2.44
1992	5,672.4	0.92	43.60	2.09	60.80	1.04	47.80	1.10	12.10	2.68	14.96	2.25
1993	5,901.8	0.93	47.20	1.78	69.40	1.04	48.20	1.09	14.50	2.07	16.26	1.71
1994	6,374.4	0.96	51.30	1.57	75.50	1.02	54.70	1.07	18.00	1.81	16.14	1.17
1995	6,674.4	0.97	64.60	1.31	83.50	1.02	60.00	1.03	21.00	1.44	22.64	1.13
1996	7,161.2	1.00	70.90	1.00	95.10	1.00	65.60	1.00	23.60	1.00	30.19	1.00
1997	7,701.8	1.02	76.70	0.78	106.60	0.97	73.00	0.99	26.20	0.69	33.68	0.71
1998	8,013.3	1.01	88.51	0.57	123.41	0.96	83.60	0.97	30.40	0.48	36.53	0.48

Notes: Values are in billions of current dollars. All price indexes are normalized to 1.0 in 1996.

Table B-1

Investment and Capital Stock by Asset Type and Class

Asset	1998 Geometric Depreciation Rate	1998 Investment ($M, current)	1998 Capital Stock ($M, current)
Total Capital	NA		27,954.7
Fixed Reproducible Assets	NA	4,161.7	20,804.2
Equipment and Software	829.1	4,082.0	
Household furniture	0.1375	2.3	13.1
Other furniture	0.1179	37.6	224.4
Other fabricate d metal products	0.0917	15.9	134.5
Steam engines	0.0516	2.7	60.1
Internal combustion engines	0.2063	1.6	6.9
Farm tractors	0.1452	10.8	60.7
Construction tractors	0.1633	2.9	15.3
Agricultural machinery, except tractors	0.1179	13.1	89.2
Construction machinery, except tractors	0.1550	20.6	99.5
Mining and oil field machinery	0.1500	2.4	15.6
Metalworking machinery	0.1225	37.1	228.6
Special industry machinery, n.e.c.	0.1031	38.6	288.7
General industrial, including materials handling, equipment	0.1072	34.5	247.5
Computers and peripheral equipment	0.3150	88.5	164.9
Service industry machinery	0.1650	17.9	92.0
Communication equipment	0.1100	83.6	440.5
Electric al transmission, distribution , and industrial apparatus	0.0500	26.7	313.0
Household appliances	0.1650	1.5	6.9
Other electrical equipment, n.e.c.	0.1834	15.2	64.5
Trucks, buses, and truck trailers	0.1917	104.5	367.0
Autos	0.2719	19.4	70.2
Aircraft	0.0825	23.0	174.5
Ships and boats	0.0611	3.0	48.4
Railroad equipment	0.0589	5.3	69.1
Instruments (Scientific & engineering)	0.1350	30.9	172.6
Photocopy and related equipment	0.1800	22.6	103.0
Other nonresidential equipment	0.1473	35.4	184.3
Other office equipment	0.3119	8.4	24.5
Software	0.3150	123.4	302.4
Non–Residential Structures	2,271.3	5,430.6	
Industrial buildings	0.0314	36.4	766.6
Mobile structures (office s)	0.0556	0.9	9.8
Office buildings	0.0247	44.3	829.8
Commercial warehouses	0.0222	0.0	0.0
Other commercial buildings, n.e.c .	0.0262	55.7	955.8
Religious buildings	0.0188	6.6	155.3
Educational buildings	0.0188	11.0	157.4
Hospital and institutional buildings	0.0188	17.76	355.12
Hotels and motels	0.0281	17.08	210.57
Amusement and recreational buildings	0.0300	9.14	103.55
Other nonfarm buildings, n.e.c.	0.0249	2.07	67.68

Table B-1—Continued

Asset	1998 Geometric Depreciation Rate	1998 Investment ($M, current)	1998 Capital Stock ($M, current)
Railroad structures	0.0166	5.78	210.36
Telecommunications	0.0237	13.19	282.09
Electric light and power (structures)	0.0211	12.12	490.04
Gas (structures)	0.0237	4.96	170.98
Local transit buildings	0.0237	0.00	0.00
Petroleum pipelines	0.0237	1.11	39.20
Farm related buildings and structures	0.0239	4.59	202.73
Petroleum and natural gas	0.0751	22.12	276.99
Other mining exploration	0.0450	2.03	38.96
Other nonfarm structures	0.0450	6.39	107.70
Railroad track replacement	0.0275	0.00	0.00
Nuclear fuel rods	0.0225	0.00	0.00
Residential Structure s	363.18	8,309.62	
1–to–4–unit home s	0.0114	240.27	5,628.27
5–or–more–unit homes	0.0140	21.11	871.81
Mobile homes	0.0455	14.64	147.17
Improvements	0.0255	86.29	1,634.15
Other residential	0.0227	0.87	28.23
Consumers Durables	698.20	2,981.97	
Autos	0.2550	166.75	616.53
Trucks	0.2316	92.53	327.85
Other (RVs)	0.2316	18.63	64.98
Furniture	0.1179	56.02	372.26
Kitchen Appliance	0.1500	29.83	161.75
China, Glassware	0.1650	29.65	141.44
Other Durable	0.1650	64.03	309.67
Computers and Software	0.3150	30.40	52.30
Video, Audio	0.1833	75.15	289.22
Jewelry	0.1500	44.58	228.38
Ophthalmic	0.2750	16.53	53.44
Books and Maps	0.1650	25.34	132.51
Wheel Goods	0.1650	48.76	231.66
Land	0.0000	5,824.18	
Inventories	0.0000	1,326.31	

SOURCE: BEA (1998a, 1999b, 1999c) and author calculations.

NOTE: Equipment and Software and Other nonresidential equipment includes NIPA residential equipment.

Table B-2

Total Capital Stock and High– Tech Assets

	Total Stock of Capital and CD Assets		Computer Capital Stock		Software Capital Stock		Communications Capital Stock		Computer & Software CD Stock	
Year	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price
1959	1,300.3	0.17	0.00	0.00	0.00	0.00	9.97	0.47	0.00	0.00
1960	1,391.0	0.18	0.20	697.30	0.10	0.61	11.11	0.47	0.00	0.00
1961	1,478.5	0.18	0.40	522.97	0.27	0.62	12.53	0.47	0.00	0.00
1962	1,583.6	0.19	0.50	369.16	0.39	0.63	14.06	0.46	0.00	0.00
1963	1,667.7	0.19	0.95	276.29	0.67	0.63	15.50	0.46	0.00	0.00
1964	1,736.0	0.19	1.44	229.60	0.97	0.64	16.99	0.47	0.00	0.00
1965	1,848.3	0.19	2.01	188.74	1.37	0.65	18.56	0.47	0.00	0.00
1966	2,007.7	0.20	2.67	132.70	1.95	0.66	20.69	0.47	0.00	0.00
1967	2,150.6	0.21	3.38	107.71	2.55	0.67	23.21	0.49	0.00	0.00
1968	2,394.9	0.22	3.88	92.00	3.09	0.68	26.38	0.51	0.00	0.00
1969	2,670.4	0.24	4.81	83.26	3.98	0.70	30.57	0.54	0.00	0.00
1970	2,874.8	0.24	5.66	74.81	5.12	0.73	35.16	0.57	0.00	0.00
1971	3,127.9	0.26	5.75	56.98	5.91	0.73	39.66	0.60	0.00	0.00
1972	3,543.0	0.28	6.68	45.93	6.86	0.73	43.77	0.62	0.00	0.00
1973	4,005.0	0.30	7.83	43.53	8.04	0.75	48.30	0.64	0.00	0.00
1974	4,250.3	0.31	8.28	35.55	9.77	0.80	55.98	0.69	0.00	0.00
1975	4,915.0	0.35	8.85	32.89	11.89	0.85	64.49	0.76	0.00	0.00
1976	5,404.1	0.37	9.46	27.47	13.52	0.87	71.56	0.80	0.00	0.00
1977	6,151.9	0.41	11.34	23.90	15.01	0.89	76.27	0.78	0.00	0.00
1978	7,097.4	0.45	12.86	16.17	17.00	0.90	88.54	0.81	0.10	33.68
1979	8,258.3	0.50	17.50	13.40	21.01	0.95	101.62	0.83	0.17	32.81
1980	9,407.4	0.56	21.85	10.46	25.93	1.01	122.33	0.88	0.28	22.11
1981	10,771.2	0.62	30.26	9.19	31.72	1.07	146.61	0.96	0.56	18.79
1982	11,538.6	0.66	37.45	8.22	38.14	1.12	168.74	1.01	1.71	15.12
1983	12,033.2	0.67	45.29	6.86	44.40	1.13	185.59	1.03	3.73	10.71

Table B-2—Continued

	Total Stock of Capital and CD Assets		Computer Capital Stock		Software Capital Stock		Communications Capital Stock		Computer & Software CD Stock	
Year	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price
1984	13,247.3	0.71	56.70	5.55	52.68	1.14	207.81	1.07	5.25	9.41
1985	14,837.5	0.77	66.72	4.72	61.66	1.13	228.43	1.09	6.21	8.68
1986	15,985.5	0.81	72.77	4.06	69.38	1.12	246.93	1.10	8.41	6.54
1987	17,137.5	0.85	78.26	3.46	79.17	1.12	262.59	1.10	11.40	5.91
1988	18,632.2	0.90	87.79	3.21	91.54	1.14	280.64	1.10	15.35	5.41
1989	20,223.2	0.96	99.26	3.00	105.64	1.11	297.05	1.10	18.06	5.02
1990	20,734.0	0.96	100.29	2.72	121.57	1.09	311.95	1.11	19.30	4.22
1991	21,085.3	0.97	99.42	2.45	140.37	1.10	324.37	1.11	22.97	3.53
1992	21,296.9	0.96	101.84	2.09	151.41	1.04	334.48	1.10	24.05	2.68
1993	21,631.7	0.96	106.68	1.78	173.39	1.04	342.48	1.09	27.20	2.07
1994	22,050.0	0.96	115.74	1.57	191.63	1.02	353.46	1.07	34.28	1.81
1995	23,346.7	0.99	130.78	1.31	215.13	1.02	362.23	1.03	39.71	1.44
1996	24,300.2	1.00	139.13	1.00	239.73	1.00	380.00	1.00	42.49	1.00
1997	26,070.4	1.04	150.57	0.78	266.63	0.97	407.58	0.99	46.20	0.69
1998	27,954.7	1.08	164.87	0.57	302.41	0.96	440.52	0.97	52.30	0.48

Notes: Values are in billions of current dollars. Total capital stock includes reproducible assets, consumers' durable assets (CD), land, and inventories. All price indexes are normalized to 1.0 in1996.

Table B–3

Total Capital Services and High–Tech Asset s

Year	Total Service Flow from Capital and CD Assets		Computer Capital Service Flow		Software Capital Service Flow		Communications Capital Service Flow		Computer and Software CD Service Flow	
	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price
1959	214.7	0.32	0.00	0.00	0.00	0.00	2.55	0.50	0.00	0.00
1960	183.7	0.26	0.05	407.59	0.02	0.64	2.65	0.47	0.00	0.00
1961	192.3	0.26	0.25	602.38	0.08	0.61	2.85	0.45	0.00	0.00
1962	211.9	0.28	0.41	480.68	0.15	0.65	3.44	0.48	0.00	0.00
1963	241.7	0.30	0.56	291.73	0.22	0.60	3.32	0.42	0.00	0.00
1964	260.2	0.31	0.77	196.86	0.34	0.59	3.68	0.42	0.00	0.00
1965	289.2	0.32	1.15	169.47	0.52	0.64	4.73	0.50	0.00	0.00
1966	315.4	0.33	1.99	161.83	0.74	0.65	5.00	0.48	0.00	0.00
1967	333.8	0.33	2.13	103.65	1.03	0.68	5.14	0.45	0.00	0.00
1968	330.2	0.31	2.40	81.43	1.29	0.69	5.43	0.44	0.00	0.00
1969	349.2	0.31	2.54	63.64	1.57	0.69	6.02	0.44	0.00	0.00
1970	382.5	0.33	3.27	61.40	2.09	0.74	7.23	0.48	0.00	0.00
1971	391.4	0.32	4.83	68.40	2.83	0.83	8.34	0.51	0.00	0.00
1972	439.6	0.35	4.44	45.09	3.01	0.77	8.86	0.51	0.00	0.00
1973	517.9	0.38	4.02	30.87	3.47	0.77	12.48	0.68	0.00	0.00
1974	546.6	0.38	6.04	36.38	3.99	0.78	11.48	0.58	0.00	0.00
1975	619.2	0.42	5.36	26.49	5.17	0.88	13.41	0.64	0.00	0.00
1976	678.1	0.44	6.01	24.25	5.60	0.84	13.61	0.62	0.00	0.00
1977	742.8	0.47	6.35	19.16	6.26	0.86	22.37	0.94	0.00	0.00
1978	847.5	0.51	10.71	20.84	7.31	0.91	19.02	0.72	0.02	17.84
1979	999.1	0.57	10.45	12.30	8.19	0.89	26.30	0.89	-0.07	19.01
1980	1,026.9	0.56	15.03	10.96	9.99	0.93	23.94	0.72	0.20	25.93
1981	1,221.4	0.66	15.92	7.33	11.76	0.94	23.89	0.64	0.25	13.90

Table B–3

Year	Total Service Flow from Capital and CD Assets		Computer Capital Service Flow		Software Capital Service Flow		Communications Capital Service Flow		Computer and Software CD Service Flow	
	Value	Price	Value	Price	Value	Price	Value	Price	Value	Price
1982	1,251.7	0.65	17.29	5.47	12.54	0.87	25.32	0.62	0.74	11.96
1983	1,359.1	0.71	22.77	5.06	15.11	0.92	29.54	0.67	2.07	10.39
1984	1,570.1	0.79	30.79	4.54	19.02	0.99	33.20	0.70	2.37	6.07
1985	1,660.5	0.79	33.72	3.43	22.41	0.99	39.30	0.77	2.70	4.93
1986	1,559.9	0.71	36.44	2.82	25.88	0.99	43.39	0.79	4.84	5.61
1987	1,846.6	0.80	45.07	2.76	31.84	1.07	55.49	0.94	4.91	3.54
1988	2,185.3	0.89	43.85	2.18	37.72	1.11	67.22	1.07	6.65	3.24
1989	2,243.0	0.89	47.89	1.97	45.96	1.16	67.90	1.02	7.89	2.85
1990	2,345.0	0.90	53.28	1.89	51.07	1.10	69.86	1.00	10.46	2.97
1991	2,345.8	0.88	52.65	1.69	54.07	1.01	66.05	0.91	11.66	2.44
1992	2,335.4	0.86	57.69	1.60	69.11	1.12	70.72	0.94	14.96	2.25
1993	2,377.4	0.85	62.00	1.42	69.32	0.98	80.23	1.02	16.26	1.71
1994	2,719.5	0.94	63.16	1.17	84.14	1.05	89.16	1.09	16.14	1.17
1995	2,833.4	0.94	77.77	1.11	89.18	0.99	101.18	1.17	22.64	1.13
1996	3,144.4	1.00	96.36	1.00	101.46	1.00	92.91	1.00	30.19	1.00
1997	3,466.3	1.05	103.95	0.77	119.80	1.04	100.13	1.00	33.68	0.71
1998	3,464.8	0.99	118.42	0.61	128.32	0.97	103.35	0.94	36.53	0.48

NOTE: Values are in billions of current dollars. Service prices are normalized to 1.0 in 1996. Total service flows include reproducible assets, consumers' durable assets (CD), land, and inventories. All price indexes are normalized to 1.0 in 1996.

Table C-1

Labor Input

	Labor Input							
Year	Price	Quantity ($B) (1996 $)	Value ($B) (Curr. $)	Quality	Employment (000)	Weekly Hours	Hourly Compensation ($)	Hours Worked (000,000)
1959	0.15	1,866.7	269.8	0.82	58,209	38.0	2.3	115,167
1960	0.15	1,877.5	289.1	0.82	58,853	37.7	2.5	115,403
1961	0.16	1,882.0	297.7	0.83	58,551	37.4	2.6	113,996
1962	0.16	1,970.7	315.3	0.86	59,681	37.5	2.7	116,348
1963	0.16	2,000.2	320.4	0.86	60,166	37.5	2.7	117,413
1964	0.17	2,051.4	346.2	0.87	61,307	37.4	2.9	119,111
1965	0.18	2,134.8	375.1	0.88	63,124	37.4	3.0	122,794
1966	0.19	2,226.9	413.7	0.89	65,480	37.1	3.3	126,465
1967	0.19	2,261.8	429.3	0.90	66,476	36.8	3.4	127,021
1968	0.21	2,318.8	480.8	0.91	68,063	36.5	3.7	129,194
1969	0.22	2,385.1	528.6	0.91	70,076	36.4	4.0	132,553
1970	0.24	2,326.6	555.6	0.90	69,799	35.8	4.3	130,021
1971	0.26	2,318.3	600.2	0.90	69,671	35.8	4.6	129,574
1972	0.28	2,395.5	662.9	0.91	71,802	35.8	5.0	133,554
1973	0.29	2,519.1	736.4	0.91	75,255	35.7	5.3	139,655
1974	0.32	2,522.2	798.8	0.91	76,474	35.0	5.7	139,345
1975	0.35	2,441.8	852.9	0.92	74,575	34.6	6.3	134,324
1976	0.38	2,525.6	964.2	0.92	76,925	34.6	7.0	138,488
1977	0.41	2,627.2	1,084.9	0.92	80,033	34.6	7.5	143,918
1978	0.44	2,783.7	1,232.4	0.93	84,439	34.5	8.1	151,359
1979	0.48	2,899.6	1,377.7	0.93	87,561	34.5	8.8	157,077
1980	0.52	2,880.8	1,498.2	0.94	87,788	34.1	9.6	155,500
1981	0.55	2,913.8	1,603.9	0.94	88,902	33.9	10.2	156,558

Table C-1

	Labor Input							
Year	Price	Quantity ($B) (1996 $)	Value ($B) (Curr. $)	Quality	Employ-ment (000)	Weekly Hours	Hourly Compen-sation ($)	Hours Worked (000,000)
1982	0.60	2,853.3	1,701.6	0.94	87,600	33.6	11.1	153,163
1983	0.64	2,904.9	1,849.0	0.94	88,638	33.9	11.9	156,049
1984	0.66	3,095.5	2,040.2	0.95	93,176	34.0	12.4	164,870
1985	0.69	3,174.6	2,183.5	0.95	95,410	33.9	13.0	168,175
1986	0.75	3,192.8	2,407.1	0.95	97,001	33.5	14.2	169,246
1987	0.74	3,317.1	2,464.0	0.96	99,924	33.7	14.1	174,894
1988	0.76	3,417.2	2,579.5	0.96	103,021	33.6	14.3	179,891
1989	0.80	3,524.2	2,827.0	0.96	105,471	33.7	15.3	184,974
1990	0.84	3,560.3	3,001.9	0.97	106,562	33.6	16.1	186,106
1991	0.88	3,500.3	3,081.4	0.97	105,278	33.2	16.9	181,951
1992	0.94	3,553.4	3,337.0	0.98	105,399	33.2	18.3	182,200
1993	0.95	3,697.5	3,524.4	0.99	107,917	33.5	18.8	187,898
1994	0.96	3,806.4	3,654.6	0.99	110,888	33.6	18.9	193,891
1995	0.98	3,937.5	3,841.2	1.00	113,707	33.7	19.3	199,341
1996	1.00	4,016.8	4,016.8	1.00	116,083	33.6	19.8	202,655
1997	1.02	4,167.6	4,235.7	1.01	119,127	33.8	20.3	209,108
1998	1.06	4,283.8	4,545.7	1.01	121,934	33.7	21.3	213,951

The Internet and the New Energy Economy

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From 1996 through 1999, the U.S. experienced an unprecedented 3.2% annual reduction in energy intensity. This is four times the rate of the previous 10 years and more than 3 times higher than the rate projected by traditional energy forecastors. There is increasing data and analysis to support the view that there is a connection between the recent reductions in energy intensity and the astonishing growth in Information Technology (IT) and the Internet Economy.

Growth in the Internet Economy can cut energy intensity in two ways. First, the IT sector is less energy-intensive than traditional manufacturing, so growth in this sector engenders less incremental energy consumption. Second, the Internet Economy appears to be increasing efficiency in every sector of the economy, which is the primary focus of this paper. The impact of the Internet economy on manufacturing, buildings, and transportation are all explored. The paper also considers the implications for growth in energy consumption and greenhouse gas emissions during the next ten years. This is a time when the Internet Economy is expected to grow rapidly and when the Internet is expected to be used to directly save energy through remote energy management of commercial and residential buildings.

Finally, there has been an argument put forward by two analysts, Mark Mills and Peter Huber, that the Internet is using a large and rapidly growing share of the nation's electricity, which in turn is supposedly driving an acceleration of overall U.S. electricity demand. Their numbers have very been widely quoted by financial analysts, major corporations, and the media. However, it is based on seriously faulty analysis and is inconsistent with recent national data, so all projections based on that analysis should be viewed with extreme caution.

[1]Note that the contents present the views of their authors, not necessarily those of the Department of Energy, RAND, or any other organization with which the authors may be affiliated.

Trends Affecting Energy Intensity

In the era of low-energy prices preceding the early 1970s, the energy efficiency of many household, transportation, and industrial technologies in United States improved little. As a result, energy demand and gross domestic product (GDP) in United States historically grew in lockstep: a 3% increase in GDP meant nearly a 3% increase in energy demand. The energy intensity of the economy (energy consumed per dollar GDP) declined only very slowly from 1950 to the early 1970s. There was a widespread view in the country that this linkage was unchangeable, that energy was essential for economic growth. There was little recognition that energy efficiency could break that trend without sacrificing economic growth.[2]

The inextricable connection between energy and economic growth came to an abrupt end with the Arab oil embargo of 1973-1974. From 1973 to 1986, GDP grew 35% in real terms while the nation's consumption of primary energy remained frozen at about 74 quadrillion BTUs (or quads). One third of the dramatic shift in energy intensity during this period was due to structural changes, such as declining share of economic activity in energy-intensive industries and increasing shares in the less energy-intensive service sector. Two thirds was due to increases in energy efficiency throughout the economy as a whole.[3]

Following the crisis, Americans bought more fuel-efficient cars and appliances, insulated their homes, and adjusted thermostats. Businesses retrofitted their buildings with more efficient heating and cooling equipment and installed energy management systems. Factories adopted more efficient manufacturing processes and purchased more efficient motors. These investments in more efficient technologies were facilitated by higher energy prices, by government policies and programs, and behavioral changes resulting from concerns about availability of energy and dependence on Persian Gulf oil.

The nation's energy intensity routinely declined by 2% per year during the years from 1973 to 1986, and some years intensity even declined by over 3%. Starting in 1986, energy prices began a descent in real terms that has continued to the present, and government investments in energy R&D and deployment programs

[2]This historical discussion is based on Brown, Levine, Romm, Rosenfeld, and Koomey, "Engineering-Economic Studies of Energy Technologies to Reduce Greenhouse Gas Emissions: Opportunities and Challenges," *Annual Raeview of Energy and Environment*, 1998, pp. 287-385.

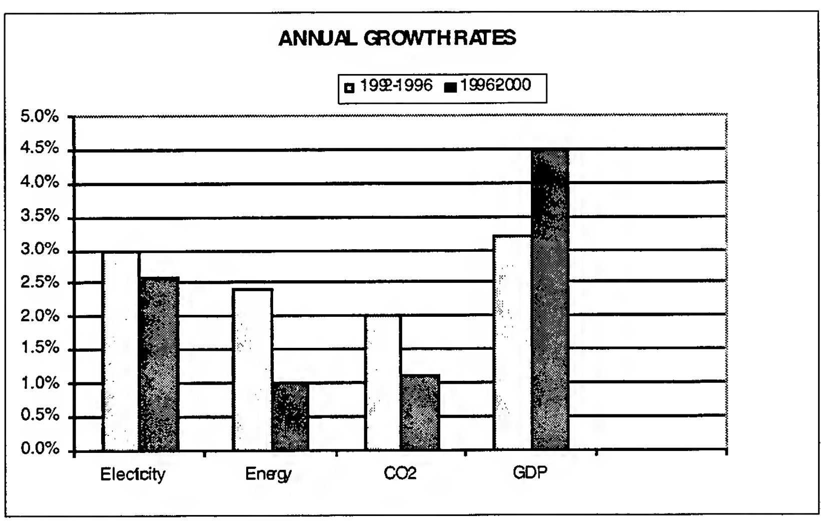
[3]Skip Laitner, "The Information and Communication Technology Revolution: Can it be Good for Both the Economy and the Climate?" U.S. Environmental Protection Agency. Washington, DC. December 1999.

have declined. These trends have contributed to a growth in energy demand from 74 quads in 1986 to 94 quads in 1996. Because of the comparable growth in GDP over the same period, the energy intensity of the economy declined less than 1% per year over the ten-year period.

Recent Drops in Energy Intensity

In the late 1990s, a startling shift appeared in the statistics. The nation's energy intensity dropped 3.7% in 1997 and 3.9% in 1998. It is unprecedented for the U.S. economy to see such improvements in energy intensity during a period of low energy prices and relatively low public awareness of energy issues. The nation had two years of economic growth totaling 9%, yet energy use in 1998 was hardly changed from its 1996 levels, just slightly more than 94 quads. In 1999, energy intensity dropped by 2%, and current data suggest that energy intensity will drop by over 3% in 2000 and that GHG emissions will continue to grow at a rate much slower than Energy Information Administration (EIA) projected.[4]

Looking at the recent data another way, if we consider what might be called the immediate pre-Internet era (1992-1996), GDP growth averaged 3.2% a year, while



[4]Energy Information Administration (EIA) projected in December 1999 that CO2 emissions would rise 2.3% in 1999. EIA, *Annual Energy Outlook 2000*, U.S. Department of Energy (DOE), Washington, DC, December 1999. Their current "flash" estimate is that 1999 saw a 1% rise in CO2 emissions. EIA, "U.S. Carbon Dioxide Emissions from Energy Sources 1999 Flash Estimate," DOE, Washington, DC, June 2000.

energy demand grew 2.4% a year. In the Internet era (1996-2000), GDP growth is averaging over 4% a year, while energy demand is growing only 1% a year. This is a remarkable change—higher GDP growth and lower energy growth. From the point of view of greenhouse gases, the immediate pre-Internet era saw 2% annual rises in carbon dioxide emissions, while the Internet era has seen rises of slightly over 1%.

The recent remarkable declines in U.S. energy intensity have motivated the Center for Energy and Climate Solutions (CECS) to think about what big changes might be happening in the U.S. economy that could be having such a big effect and whether those changes are likely to continue and possibly grow. The purpose here is not to explain in detail all of reasons for the sharp drop in energy intensity over the past two years. There is a great deal of year-to-year fluctuation in the change in energy intensity, which is due to a variety of factors. Weather, for instance, can play a big role. In 1998, the country experienced both a very warm winter (which reduces the consumption of natural gas and other heating fuels) and one of the hottest summers on record (which increases the consumption of electricity for air conditioning). The weather was responsible for perhaps 0.5% out of the 3.8% average annual drop in energy intensity in 1997 and 1998.[5]

Other relevant factors include the rebound in federal investment in energy efficiency in the 1990s, though a countervailing trend has been the decline in demand-side management funding by utilities. Slowdown in the Asian economies also reduced exports (and hence U.S. manufacturing). Unfortunately, EIA requires a considerable amount of time to collect and analyze key data on energy consumption trends by sector (such as buildings and manufacturing), so it will be a few years before we have a detailed understanding of what is going on. Disentangling all of these factors is beyond the scope of this paper. The goal here is in examining some key trends that may well be having an impact today and are likely to play an important role in the next decade. The impact of Information Technology and the Internet economy is the key trend examined here.

The New Energy Economy: A Fundamental Change

In a 1999 report, CECS examined the relationship between the economic growth and a new trend in energy intensity, and concluded that the Internet economy could fundamentally and permanently alter the store relationship—allowing

[5]Laitner, 1999, op. cit.

faster growth with less energy use than we have seen in the past. We labeled this a "New Energy Economy, " and predicted "annual improvements in energy intensity of 1.5%—and perhaps 2.0% or more." Although we were criticized by some, including EIA, for this prediction, the most recent data cited above are strongly suggestive that a fundamental change is occurring in the economy and that our scenario may well be a key part of the explanation. It now appears that even EIA is going to substantially increase its projection for annual energy intensity gains this decade.[6]

Our report "The Internet Economy and Global Warming: A Scenario of the Impact of E-commerce on Energy and the Environment," remains the most comprehensive analyses to date on the nature and scope of the Internet's effect on energy consumption and greenhouse gas emissions. It is available online at www.cool-companies.org.

Analysis by EPA and the Argonne National Laboratory suggests that one third to one half of the recent improvements in energy intensity are "structural."[7] Structural gains occur when economic growth shifts to sectors of the economy that are not particularly energy intensive—such as the IT sector, including computer manufacturing and software—as opposed to more energy-intensive sectors, including chemicals, pulp and paper industry, and construction.

More importantly, the remaining one-half to two-thirds of the improvement in our economy's use of energy comes from overall efficiency throughout the system as a whole, occurring when businesses change their activities in ways that reduce energy use relative to their output of goods and services. For example, a factory might use more efficient motors on its assembly line or better lighting in its buildings, or a chemical manufacturer might redesign a process for making a chemical to cut the energy used per pound of product.

According to our findings, the Internet economy itself seems to be generating both structural and efficiency gains. If companies put their stores on the Internet, rather than constructing new retail buildings, which would represent an Internet structural, gain. If that same company used the Internet to more effectively manage its existing supply chain, it would be an efficiency gain. The following is a brief summary of our principal findings, with some relevant updated data and analysis. A longer discussion of each of these sectors—manufacturing, buildings, transportation—can be found in the original report.

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[6]Personal Communications with Skip Laitner, EPA, September 2000.

[7]G. Boyd and S. Laitner, *Recent Tends in U.S. Energy Intensity*, U.S. EPA, Washington D.C., 2000.in

Internet Makes Manufacturing More Efficient

The Internet Economy appears to be causing a broad improvement in manufacturing efficiency. Federal Reserve Board Chairman Alan Greenspan told Congress in June "Newer technologies and foreshortened lead-times have, thus, apparently made capital investment distinctly more profitable, *enabling firms to substitute capital for labor and other inputs far more productively than they could have a decade or two ago.*"[8]

As traditional manufacturing and commercial companies put their supply chain on the Internet, and reduce inventories, overproduction, unnecessary capital purchases, paper transactions, mistaken orders, and the like, they achieve greater output with less energy consumption.

Between 1990 and 1998, Dell computer grew considerably while simultaneously moving many of its operations to the Internet. Its sales increased 36-fold, but its physical assets (i.e. buildings, factories) rose by only a factor of four.[9] IBM has used the Internet to improve communication between factories, marketing and purchasing departments. If one factory cannot meet its production schedule or if demand suddenly rises, IBM finds out in time to increase production at another factory. This has allowed the company to better utilize its existing manufacturing capacity and thus avoid making additional investments to meet increased volume requirements. By mid-1998, the reduced investment and operating costs had saved the company $500 billion.[10] Many, many companies from General Electric to Cisco Systems, are achieving similar efficiencies.

Inventories may be the single measure of the manufacturing sector's overall efficiency. Higher inventory turnover and lower overall inventories represent a vast savings for the economy: Less new manufacturing infrastructure is required needs to be constructed, fewer excess goods need to be manufactured and then shipped to warehouses—where they are heated and cooled—and then either shipped again for ultimate sale or, in many cases surplused. Every stage of this process consumes a vast quantity of energy, in buildings, transportation, and most especially in the manufacturing of basic materials (such as the steel in the excess manufacturing capacity) and the manufacturing of finished goods.[11]

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[8]Alan Greenspan, "High-tech industry in the U.S. economy," Testimony Before the Joint Economic Committee, U.S. Congress, June 14, 1999.

[9]James Fallows, "The McCain Factor," *The Industry Standard*, February 21, 2000.

[10]Lynn Margherio et al, "The Emerging Digital Economy," Department of Commerce, April 1998.

[11]The energy used to create and transport the raw materials that a company uses may vastly exceed energy they use directly. For instance, Interface Flooring Systems calculates this "embodied energy" in raw materials for its carpet tile outstrips the energy needed to manufacture it by a factor of

The Internet is widely viewed as likely to have a large impact on inventories. As the Department of Commerce put it in July 2000, "by improving communications with suppliers and customers, IT has facilitated manufacturers, efforts to limit their inventory exposure."[12] Companies are increasingly using the internet to work together for better forecasting and restocking, using a process called Collaborative Planning Forecasting Replenishment (CPFR). Home Depot uses information technology and the Web throughout its supply chain to largely bypass the warehouse: 85% of its merchandise moves directly from the manufacturer to the storefront. The Automotive Industry Automation Group tested an internet-based supply chain management system that cut lead times 58%, a 24% improvement in inventory levels, and a 75% reduction in error rates; a similar system by Toyota is cutting in-house inventories by 28% and storage requirements in the plant by 37%, freeing space for manufacturing.

What is potential impact on the digital economy on inventories? Ernst & Young has estimated that CPFR could lead to an inventory reduction of $250 billion to $350 billion across the economy, roughly a 25% to 35% cut in finished goods inventory across the supply chain.[13]

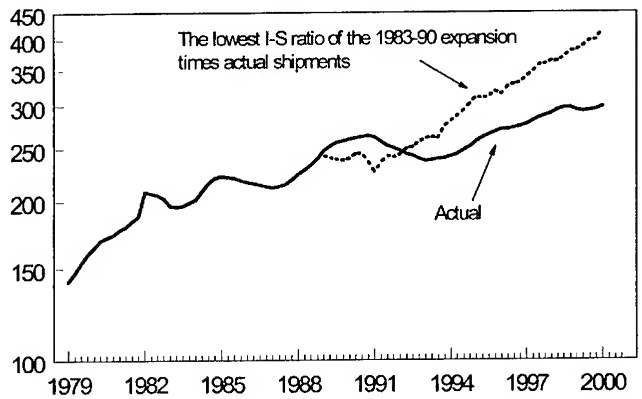
What has been achieved to date in the economy? According to the Department of Commerce July report, with the aid of IT "durable goods manufacturers have reduce their inventory ratios from 16.3% of annual shipments in 1998," which was the lowest ratio in the 1983 to 1990 expansion, "to just 12.0% in the last 12 months." The implications are enormous: "*If U.S. manufacturers of durable goods today held inventories at the 1988 inventory to sales ratio, they would be holding an additional $115 billion in inventory.*" This represents $115 billion in durable goods that were not manufactured, even as output and GDP soared. It means "companies are spared the expense of storing and securing one-third more inventories than they now hold" and "they avoid the inevitable losses from holding inventories for products that lose favor in the marketplace." This means saving the enormous energy required to make, move, and store $115 billion worth of goods.

12. That means a 4% cut in wasted product could save the equivalent of fully half the energy used in manufacturing.

[12]Economics and Statistics Administration, *Digital Economy 2000*, Department of Commerce, Washington, DC, June 2000.

[13]Andrew Wyckoff and Alessandra Colecchia, *The Economic and Social Impact of Electronic Commerce*, Organisation for Economic Co-Operation and Development (OECD), Paris, France, 1999. [Hereafter *OECD 1999*.]

Figure 7.10
Durable Goods Manufacturing Inventories
Billions of dollars



Source: ESA estimates based on Census data.

Clearly, if we continued to have significant GDP growth without significant inventory growth, that would suggest that our energy intensity gains will continue. If indeed the Ernst & Young estimate is correct, then we have not even achieved half of the inventory savings that the Internet economy will ultimately make possible.

Internet Saves Commercial Building Energy

The Internet holds the potential to increase efficiency in a variety of buildings, including retail, warehouse and storage, and office buildings. Probably the best known and most widely studied consumer e-commerce activity is book purchasing, popularized first by Amazon.com. Consider these statistics from a 1998 case study on Amazon.com to which we have added two lines of energy calculations:

Table 1

Comparison of Operating Models of Land-based Versus Online Bookstore[14]

	Traditional Superstore	Online Bookstore (Amazon.com)
Titles per Store	175,000	2,500,000
Revenue per Operating Employee	$100,000	$300,000
Annual Inventory Turnover	2-3 times	40-60 times
Sales per square foot	$250	$2,000
Rent per sq. ft.	$20	$8
Energy costs per sq. ft.	$1.10	$0.56
Energy costs per $100 of sales	$0.44	$0.03

So a plausible estimate for the ratio of commercial building energy consumption per book sold for traditional stores versus online stores is 16 to 1. So Internet energy efficiency appears to be a very powerful tool for reducing building energy intensity. The impact of e-commerce on transportation energy consumption is discussed later.

This type of efficiency gain is likely to be seen throughout a wide swath of retail buildings, not just book stores, but electronics, software, pet stores, toy stores, banks, and the like. Mark Borsuk, Executive Director of the Real Estate Transformation Group, wrote recently that Wall Street will "demand that retailers curtail new store growth, reduce the number of locations, and shrink store size."[15]

What is the ultimate impact in the retail sector likely to be? A 1999 OECD report on the impact of e-commerce estimated that "economy-wide efficiency gains" from a "business-to-consumer scenario" could "reduce total wholesale and retail trade activity for consumer expenditures by 25 percent":

It was assumed that this reduction would lead to a decline in the use (cost) of buildings and related services (construction, real estate, utilities) by 50 percent, or a 12.5 percent decline in total for retail and wholesale trade.[16]

These savings, plus savings in labor and capital, "leads to a reduction in aggregate distribution cost of about" 5.2% and in "total economy-wide cost by about" 0.7%. The study notes that "While small, this is still a considerable gain,

[14]The non-energy parts of this table are from Mohan Sawhney and David Contreras, "Amazon.com—Winning the Online Book Wars," case study, J.L. Kellogg Graduate School of Management, Northwestern University, p. 26, http://sawhney.kellogg.nwu.edu/. The case study cites Morgan Stanley Research as the source of the data in the table.

[15]Mark Borsuk, "Under the Knife." *The Industry Standard*. January 14, 2000.

[16]Hereafter *OECD 1999*.

since a reduction in these costs is a rough proxy for productivity gains [total factor productivity]."

It is interesting that so much of the cost savings in this estimate are in the energy area: construction and utilities. So, if total economy-wide cost is reduced on the order of 0.7% from business-to-consumer e-commerce, then it seems plausible to estimate a concomitant reduction in energy costs of the same fraction. That would mean energy cost savings of $4 to $5 billion, most of which would be in the commercial buildings sector and industrial sector (i.e. construction). *A 12.5% decline in the use of retail buildings alone represents about 1.5 billion square feet of commercial building space no longer needed.*[17]

As for office space, the Internet has two key impacts. First, companies like IBM and AT&T are cutting office space for workers who spend a great deal of time with customers outside the office, such as sales and service.[18] They give those "Internet telecommuters" laptops, put critical data on their corporate intranets, and then the workers spend their time working on the road and at home. If they need to come into work they can email in to reserve shared office or meeting space. Today, for example, virtually all of IBM's sales force — nearly 17% of their total workforce worldwide — can operate independent of a traditional workplace, helping cut occupancy cost per employee by one-third. With roughly the same number of total workers in 2002 as in 1998, AT&T expects to cut total square footage from about 32 million square feet to 21 million square feet. Each Internet telecommuter saves about 175 square feet per worker times 20 kWh per square foot or 3500 kWh a year. We would not be surprised if the incremental home electricity consumption were 500 kWh based on telecommuters spending about one third of their time at home. The *net* savings would be 3000 kWh a year, worth about $200 a year.

Second, the Internet is driving a boom in purely home-based work. International Data Corporation has estimated that the number of home offices is growing by about three million a year. IDC projects the number of home offices with PCs on the Internet will grow from 12 million in 1997 to 30 million in 2002 (IDC 1999). This increase in home offices reduces the amount of incremental office space required for an increment in GDP. We believe that translates into a net savings in

[17]This assumes that retail space is approximated by using the figures for total mercantile and service floorspace, which was 12.7 billion square feet in 1995. *EIA 1998*. As for warehousing, even accounting for the increase in warehouses by internet retailers, the net result might be to eliminate the need for another one billion square feet of commercial warehouses and on-site storage at manufacturing facilities. Net energy savings from changes in warehousing may be modest, however, since new warehouses consume far more energy than the average warehouse.

[18]Mahlon Apgar IV, "The Alternative Workplace: Changing Where and How People Work," *Harvard Business Review*, May-June 1998, pp. 121-136.

building energy consumption. A worker in a traditional small office building (with an average 300 square feet of space) would probably be consuming upwards of 6000 kWh a year. Her incremental home-based electricity consumption is perhaps 1500 kWh, yielding a *net* savings of more than 4000 kWh (Romm 1999).

Suppose that from 1997 to 2007 the Internet leads to an additional one million home offices each year. Suppose that half of those are Internet telecommuters and half are Internet entrepreneurs and that they avoid on average 150 square feet and 300 square feet of office space respectively. That would avoid the need for more than 2 billion square feet of office space by 2007.

A very preliminary estimate of the potential *net* impact of the Internet on Buildings is that by 2007, business-to-consumer and business-to-business e-commerce together could avoid the need for 1.5 billion square feet of retail space—about 5 percent of the total—and up to 1 billion square feet of warehouses. Internet technology may also eliminate as much as 2 billion square feet of commercial office space, the equivalent of almost 450 Sears Towers, along with all the lighting, heating and cooling that goes with it.

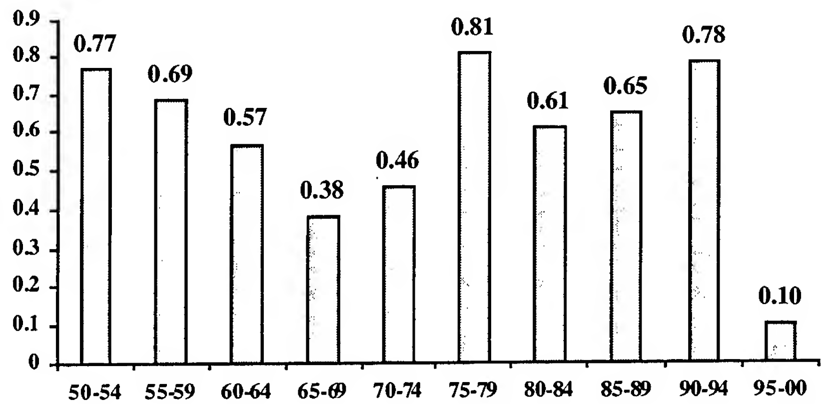
Energy savings from operations and maintenance alone for these "unbuildings" total 53 billion kilowatt hours per year, about 13 percent of total electricity growth projected under old, business-as-usual scenarios. That equals the output of 21 average power plants, plus 67 billion cubic feet of natural gas. Expressed in terms of the global warming issue, this Internet "unbuilding" scenario would prevent the release of 35 million metric tons of greenhouse gases.[19]

Is there any evidence that we have entered a period in which we can have GDP growth without the need for as many new buildings, particular commercial office buildings? We believe so. Consider a recent analysis by James Paulsen, Chief Information Officer, of Wells Capital Management.[20] According to this analysis, "during the 45 years after World War II until 1995, on average every 1 percent change in real GDP growth produced a 0.65 percent change in job growth." But in the last five years, the job impact of GDP growth has virtually stopped: "Since 1995, for every one percent rise in real GDP growth, job growth has increased by only 0.1 percent—the weakest job impact in the postwar period!"

[19] Avoided construction of all those buildings saves the equivalent of 10 power plants worth of energy, and another 40 million metric tons of greenhouse pollution. By 2010, e-materialization of paper, construction, and other activities could reduce U.S. industrial energy and GHG emissions by more than 1.5%.

[20] James Paulsen, "Economic and Market Perspective," September 2000, Wells Capital Management.

This is strongly suggestive that we have entered a where GDP growth does not require as much commercial office buildings (and storage for inventories and retail stores) as has historically been the case. We have not yet seen data on



Percentage Change in Annual U.S. Job Growth Due to a 1-Percent Change i n Real GDP Growth (by 20-quarter increments)

whether there has been an accompanying reduction or slowdown in construction, which is a very cyclical industry and subject to significant lags between supply and demand.

Internet and Transportation

The potential energy impact of the Internet Economy on the transportation sector is more of a mixed bag, with factors at play that may offset one another—potentially increasing energy intensity in some areas, but cutting it in others. If certain trends persist, however, Internet technology could lead to dramatic drops in energy in energy intensity in this sector.

The Internet holds the prospect of *increasing* energy intensity by

- Increasing delivery of products by relatively inefficient means, including overnight delivery by air and/or truck
- Increased shipping in general, as the globalization fostered by the Internet makes it easier to purchase objects from very far away
- Increasing personal (and business) travel, as people seek to meet in person the widely dispersed people they have met on the Internet

On the other hand, the Internet holds the prospect of *reducing* transportation energy intensity.

- replacing some commuting with telecommuting
- replacing some shopping with teleshopping
- replacing some air travel with teleconferencing
- enabling digital transmission or e-materialization of a variety of goods that are today shipped by truck, train and plane, including formerly printed material, software, construction materials, and the like
- improving the efficiency of the supply chain
- increasing the capacity utilization of the entire transportation system.

This sector is particularly difficult to analyze. For instance, some of the above effects are interactive and potentially offsetting: some personal shopping by car is likely to be replaced by small-package shipping. A 20-mile round-trip to purchase two 5-pound products at one or more malls consumes about one gallon of gasoline. Having those packages transported 1000 miles by truck consumes some 0.1 gallons, and much less than that if railroads carry the packages for a significant fraction of the journey.[21] Shipping the packages by air freight, however, consumes nearly 0.6 gallons. These numbers are only very rough approximations, but they make clear that the transportation energy benefits of teleshopping are only partially offset by overnight delivery of e-commerce purchases by air freight.

Even well studied areas, such as the impact of telecommuting on vehicle miles traveled (VMT), are exceedingly complicated. Further, it will be particularly difficult to disentangle trends that have been ongoing for many years—such as the rapid growth in international trade, air travel, and VMT— from any impact the Internet may have. The huge swings in the price of oil will also make analysis difficult in the short term.

Nonetheless, a few key points deserve mention. First, HBB (home-based business) workers spend less time traveling in cars (for all purposes) per day than either home-based telecommuters (HBT) or non-home-based (NHB) workers (i.e. conventional workers), according to the "first known U.S. study of HBB travel."[22] HBB spent 1.23 hours a day traveling in cars, whereas HBT spent

[21]Stacy Davis and Sonja Strang, *Transportation Energy Data Book: Edition 13,* Office of Transportation Technologies, U.S. Department of Energy, ORNL-6743, March 1993, p. 3.

[22] Patricia Mokhtarian and Dennis Henderson, "Analyzing the Travel Behavior of Home-based Workers in the 1991 CALTRANS Statewide Travel Survey," *Journal of Transportation and Statistics*, Vol.

1.39 and NHB spent 1.61. So to the extent the Internet is leading to an increase in HBBs, it will slow VMT growth.

Second, as one major study of energy use and lifestyles noted, "a minute spent traveling uses 8 and 12 times as much energy, respectively, as a minute spent in service buildings or at home."[23] Moreover, one's home is always using a fair amount of energy, even when one is traveling, whereas the family car uses energy only when it is being driven. Therefore, the incremental energy benefit of spending an extra minute online rather than traveling is even greater than 12 to 1. Some recent studies suggest that heavy Internet users (greater than five hours a week) spend less time driving than average.[24]

Third, the Internet is helping make the freight industry much more efficient. For instance, as many as half the freight trucks on the road are empty at any one time. A number of companies are auctioning off that empty space online, such as The National Transportation Exchange (NTE). Although this area is poorly studied, it seems clear that the capacity utilization of the trucking system has begun to increase. One trucking company, Yellow Freight, has already reported productivity gains of 20% from the application of IT.

The great unknown question at this point is whether or not a significant fraction of Americans will change their driving habits over the next few years once it is possible to make a critical mass of cyber-trips on the Internet. That is, will the Internet be the mall of the 21st Century?

Already, in the last two and a half years, the growth rate in vehicles miles traveled (VMT) has slowed, and the VMT to GDP ratio has dropped dramatically. In November 1999, EIA wrote of the "continued weakening of the relationship between income and travel growth."[25] Preliminary reports from the State Highway Agencies reveal that total VMT rose only 2% in 1999, the slowest growth since 1991, a recession year, and that VMT has risen only 1.6% for the first half of 2000.[26]

We suspect the Internet economy will be no worse than neutral in the transportation sector, but could well have a large positive impact. We may be

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1 No. 3, October 1998, pp. 25-41. As the authors explain, estimates for the precise number of home-based workers vary widely, in part because of different definitions used by different analysts and in part because of difficulties in measuring who is actually working at home (and the related question of how much one has to work at home to qualify as a home-based business).

[23]Lee Schipper et al, "Linking Life-Styles and Energy Use: A Matter of Time?" *Annual Review of Energy 1989*, 14:273-320.

[24]N. Nie. and L. Erbring, L. "Internet and Society, " Stanford Institute for the Quantitative Study of Society, Stanford, CA: 2000.

[25]EIA, *Short-Term Energy Outlook November*, DOE, Washington, DC, December 1999.

[26]Federal Highway Administration, "Traffic Volume Trends, May 2000," Department of Transportation, Washington, DC, September 2000.

seeing early signs of that, but it is certainly too early to tell. The impact in the buildings sector, and especially the manufacturing sector, seem likely to be beneficial. Therefore, we believe the overall impact of the Internet economy is to reduce the nation's energy intensity, perhaps significantly.

What About Energy Use by the Internet?

As to the important question of whether the Internet itself is consuming vast amounts of electricity, the facts simply—and irrefutably—fail to support such a conclusion. To begin with, the rate at which U.S. electricity demand is growing has *slowed* since the start of the Internet boom. As then EIA head Jay Hakes testified in February 2000:

From 1985 to 1995, retail electricity sales grew at a rate of 2.6% per year.... Since 1995, the use of the Internet has increased dramatically, yet retail electricity sales have grown by 2.1% per year.[27]

The immediate pre-internet era (1992-1996) saw electricity demand rise 2.9% per year. Since 1996, electricity demand has risen only 2.3% per year. And this has all occurred in spite of higher GDP growth since 1995, hotter summers (1998 was the hottest summer in four decades in terms of cooling-degree days; 1999 was the second hottest summer), and less support by utilities for demand-side management, all of which would normally lead to higher growth in electricity demand. This likely has much to do with the trends already discussed here.

It is worth examining this question in more detail because the statistics and projections presented by Peter Huber and Mark Mills have been repeated widely by financial firms, energy corporations, the news media, and policy-making circles. For instance, the president of Duke Energy's Power Services is quoted in the October 2 issue of the *Industry Standard* that "electrical demand has been outpacing GDP growth. And we believe the main reason is the Internet an electronic commerce." Republican presidential candidate George W. Bush has even used in these projections as part of the reason underlying his energy policy, released in October 2000.

Mills and Huber argue the Internet has become a major energy *consumer* because it supposedly requires a great deal of electricity to run the computers and other hardware powering the Internet economy.[28] In fact, according to recent research,

[27]EIA, "Statement of Jay Hakes before the Subcommittee On National Economic Growth," U.S. House of Representatives, Committee On Government Reform, Washington, DC, February 2, 2000.

[28]Peter Huber and Mark Mills, "Dig more coal—the PCs are coming," *Forbes*, May 31, 1999, pp. 70-72.

they appear to have significantly overestimated the energy consumption of most critical pieces of equipment.

Scientists at Lawrence Berkeley National Laboratory (LBNL) examined in detail the numbers underlying the Mills and Huber analysis, and found that the estimates of the electricity used by the Internet were high by a factor of eight.[29] Major overestimates were found in every category, including their calculations of energy used by major dot-com companies, by the nation's web servers, by telephone central offices, by Internet routers and local networks, and by business and home PCs.

The Internet does not consume 8% of U.S. electricity as Mills claims. *The Koomey et al. analysis showed that this estimate is too large by a factor of eight*. Computers, office equipment, and the like do not consume 13% of electricity, as Mills claim; a better number is 3%.

Mills and Huber assumed, for instance, that a "typical computer and its peripherals require about 1,000 watts of power." In fact, the average PC and monitor use about 150 watts of power; this dips to 50 watts or less in energy-saving mode. Laptop computers, a key growth segment, are particularly low energy users, with some using under 30 watts. Moreover, computers are getting more energy-efficient every year because of steady improvements in technology driven in part by the growing market for portable equipment (and by the IT sector's desire to reduce its environmental impact).[30] New flat screens typically use about a quarter of the energy of traditional video display terminals with cathode ray tubes.

These basic mistakes are reflected in their conclusions. Mills and Huber claim that from 1996 to 1997, the *increase* in electricity consumed by all computers used for the Internet constituted more than 1.5% of all U.S. electricity consumed that

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[29]Jonathan Koomey, Kaoru Kawamoto, Maryann Piette, Richard Brown, and Bruce Nordman. "Initial comments on *The Internet Begins with Coal*," memo to Skip Laitner (EPA), Lawrence Berkeley National Laboratory, Berkeley, CA, December 1999, available at http://enduse.lbl.gov/Projects/infotech.html. The underlying analysis is Mark Mills, *The Internet Begins with Coal: A Preliminary Exploration of the Impact of the Internet on Electricity Consumption*, The Greening Earth Society, Arlington, VA, May 1999.

[30]Typical home Internet users are online 5 to 10 hours a week (under 500 hours a year). So they consume under 100 kWh a year on the Internet, more than a factor of 10 *less than* the estimate of the *Forbes'* authors of 1000 kWh a year. And this does not even include any of the myriad potential offsets, such as a reduction in television watching, which would save a considerable amount of electricity. Long before the Internet was popular, PCs have been used at home for word processing, games, and the like. It is therefore methodologically flawed to ascribe all or even most of the electricity consumed for home PCs in general to the Internet (for a discussion of this "boundary" issue, see Koomey et al, "Initial comments on *The Internet Begins with Coal*"). Internet telecommuters and home-based businesses use the Internet considerably more than the average home user, but, as discussed in our analysis, they are probably displacing far more electricity consumption by not working in an electricity-intensive office building.

year. Yet total electricity consumption for all purposes grew slightly less than 1.4% during that period, which would imply that electricity growth for everything else equaled zero—despite economic growth of 4.5%. While we believe that the Internet reduces energy intensity, we don't believe it has quite that dramatic an effect.

But mathematical and data errors are only part of the problem. Indeed, it appears Mills and Huber have the entire Internet energy story almost completely backwards. One of the reasons why energy intensity declined so slowly from 1987 through 1996 is likely that businesses in particular purchased a great many computers and other IT equipment that consume electricity, yet generated little accompanying productivity gains to offset that increased energy use. But Internet changed all that, unleashing a storm of new productivity in every sector of the economy. By then, of course, most office desks already had computer. The added energy needed to shift PCs from traditional uses to the Internet is modest compared to its overall benefit.

Computers and the Internet may well lead to more home electricity consumption. This is part of a long-standing trend, as homes have for some time been getting bigger and more stocked with electronic equipment. But the question is, if people spend *more* time on the Internet, *what are they spending less time doing*? Some will be watching television less; others reading newspapers less; some may be printing individual items of interest to them rather than receiving entire printed catalogs or directories in the mail; others will be working at home rather than in an office building; and, potentially, some may be not be driving to work or to malls as often as before. These are all activities that would normally consume a great deal of energy and their potential displacement by home Internet use is the subject of recent analysis, which suggests that some substitution is already occurring.[31]

Direct Energy Savings by the Internet

So far this paper has focused on the potential "indirect" energy efficiency benefits of the Internet. Yet in the very near future the Internet will itself be used to save energy directly as commercial and residential buildings have their energy managed over the Internet.

Digital energy management control systems (EMCS) can continuously gather data about what is taking place in a building and how its equipment is operating,

[31]N. Nie. and L. Erbring, L. "Internet and Society, " Stanford Institute for the Quantitative Study of Society, Stanford, CA: 2000.

feeding it into a central computer used to control building systems and optimize energy performance. Energy experts at Texas A&M have shown in two dozen Texas buildings that using such an approach can cut energy use 25 percent with an 18-month payback in buildings that have already received on upgrade with the latest energy-saving equipment.[32]

Increasingly, such technologies will operate over the Internet itself. Companies like SiliconEnergy have developed software that uses the Internet for real-time data collection and analysis and. energy management. We believe energy outsourcers like Enron (discussed below) may ultimately manage hundreds if not thousands of buildings over the Internet.

The state of California is examining whether "demand-responsive" buildings may be a more cost-effective and environmentally superior strategy for dealing with peak power demand than building new generation. Currently, on hot days, California sees peak demand of 45,000 MW, of which 13,000 MW goes to air conditioning and 5,000 MW goes to commercial lighting. If a building has an energy management control system, then it could receive real-time pricing information over the Internet. On a voluntary basis and in return for a rebate from the utility, buildings could allow the indoor temperature to drift up 1 to 2 degrees Fahrenheit. This would not affect comfort much, especially since on days of predicted heat waves, the owner could precool the building. Similarly, hot days typically occur when the sun is out, so a "demand-responsive building" could also initiate some reduced lighting, both interior and exterior. This strategy could shave some 1000 MW from California's peak demand without building several new power plants. California will be launching a pilot program soon, and, if it is successful, introduce the program statewide.[33]

Many utilities have begun exploring Internet-based home energy management systems, which would give individual homeowners more control and feedback over their home energy use, or the ability to have an outside energy company or expert software system optimize their energy consumption. Early trials of remote controlled home energy management systems suggest the savings in energy bills could be as high as 10%.

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[32]Joseph Romm, *Cool Companies: How the Best Businesses Boost Profits and Productivity by Cutting Greenhouse Gas Emissions* (Washington DC: Island Press, 1999), pp. 28-30, 57-63, 77-99, 140-156.

[33]Personal communications with Arthur Rosenfeld, California Energy Commission, September 2000.

Other Key Trends Affecting U.S. Energy Consumption

This paper has focused on the impact of the Internet on U.S. energy consumption. There are a number of other trends that are likely to have a significant impact this decade, and they deserve a brief mention.

OUTSOURCING: A new trend has emerged that is revolutionizing corporate energy efficiency investments. Companies are starting to outsource their power needs altogether. In March 1999, Ocean Spray announced a $100 million deal with the energy services division of Enron. Enron will use its own capital to improve lighting, heating, cooling and motors and to invest in cogeneration. Ocean Spray will save millions of dollars in energy costs, have more reliable power and cut pollution, without putting up any of its own capital. In September 1999, Owens Corning, the fiberglass insulation manufacturer, announced a similar $1 billion deal with Enron. Other energy service companies are taking a similar approach. Some companies, like Sempra Energy Solutions, have even gone so far as to finance, build, own and manage the entire energy system of a customer.

The potential impact of this trend is enormous. Companies like Ocean Spray and Owens Corning would typically make investments in energy-efficient equipment only with a payback of a year or so. The energy companies they signed a long-term contract with, however, will make much longer-term investments, typically with a five- to seven-year payback, but sometimes as high ten years. This allows a great deal more energy efficiency to be achieved.

These energy outsourcing deals are quite new. Few engendered much investment in new capital before 1999. Yet, some energy outsourcers are signing up Fortune 1000 clients at a rapid pace. These deals will grow very rapidly in the next few years, and are likely to ultimately achieve savings well beyond that of utility-based demand-side management (DSM) programs. This is particularly true for two reasons. First, traditional DSM often focused on retrofitting individual electricity-using components, whereas outsourcing encourages a whole systems approach to efficiency covering all fuels, an approach that can achieve deeper savings at lower cost. Second, traditional DSM did not in general encourage cogeneration, as the outsourcing deals do. Indeed, when Coors outsourced its cogeneration system to Trigen, Trigen was able to cut energy costs per barrel of beer by 20%, more than twice what Coors expected. And cogeneration combined with energy efficiency can cut the energy consumption of a building or factory by 40% or more in a period of just a few years.[34]

[34] See, for instance, Romm, *Cool Companies*, pp. 117-118 and 159-162.

It is entirely possible if not likely that *within a few years, outsourcing could lead to significantly higher levels of investment in energy efficiency than achieved in the early 1990s by utilities in their DSM programs.* If this scenario comes to pass, then energy outsourcing will have a major impact on improving the nation's energy intensity in the next decade.

CORPORATE GHG COMMITMENTS: There is another recent business trend that will have lasting impact on energy consumption trends. Increasingly, major corporations are making company-wide commitments to reduce their greenhouse gas emissions. As the *Wall Street Journal* noted in an October 1999, article:

In major corners of corporate America, it's suddenly becoming cool to fight global warming.

Facing significant shifts in the politics and science of global warming, some of the nation's biggest companies are starting to count greenhouse gases and change business practices to achieve real cuts in emissions. Many of them are finding the exercise is green in more ways than one: Reducing global warming can lead to energy-cost savings.[35]

In 1999, Kodak announced in 1999 that they would reduce their greenhouse gas emissions 20% by 2004. DuPont—one of the biggest energy users in the United States—pledged publicly to reduce greenhouse gas emissions 65% compared to 1990 levels by 2010. Two thirds of those savings will come from reducing process-related greenhouse gases; the rest will come from energy. They pledged to keep energy consumption flat from 1999 to 2010 even as the company grows, and to purchase 10% renewable energy in 2010.

This year, Johnson & Johnson and IBM each joined the Climate Savers partnership with the World Wildlife Fund (WWF) and Center for Energy a Climate Solutions, pledging to make substantial energy and greenhouse emissions cuts. Several other major companies are expected to join Climate Savers in Coming months. For its Climate Savers commitment, Johnson & Johnson has pledged to reduce greenhouse gas emissions by seven percent below 1990 levels by the year 2010, with an interim goal of four percent below 1990 levels by 2005. IBM, having already achieved an estimated 20% reduction in global CO2 emissions through energy conservation efforts from 1990 through 1997, is now pledging to achieve average annual CO2 emissions reductions equivalent to 4% of the emissions associated with the company's annual energy

[35]Steve Liesman, "Dropping the Fight On Science, Companies Are Scrambling to Look a Little Greener," *Wall Street Journal*, October 19, 1999, p. B1.

use through 2004 from a baseline of 1998. Even major oil companies including BP and Shell have committed to make major emissions cuts, at least some of which will come from efficiency investments in their own facilities.

It may well be that two trends—energy outsourcing and corporate climate commitments — combine. The Center is working with a major energy service company to demonstrate that virtually any Fortune 500 company can make an outsourcing deal to reduce its energy bill, its energy intensity, and its greenhouse gas emissions, without putting up any of its own capital. Should concern over global warming continue to grow, this type of deal may become commonplace.

The Future

In the September 7, 2000 issue of the *Wall Street Journal*, Huber and Mills discuss their theory that the Internet is an electricity hog, claim that "power demands are now growing at twice the rates planned for just a few years ago," and write about "the 3%-4% annual increases in power demand that now lie ahead."[36]

As we have seen, there is no data to support these claims or projections. Quite the reverse. Since 1996, the country has had the fastest decline in its electricity intensity (amount of electricity needed to produce a dollar GDP) in decades.

What of the future? As noted, the growth rate of U.S. electricity consumption has been decelerating even in the face of much higher GDP growth. The Internet does not consume a large fraction of U.S. electricity today, nor do PCs, office equipment, and network equipment. The growth rate of power used by the Internet is much slower than the growth rate of the Internet. The Internet appears to save electricity indirectly (by making the whole economy more efficient) and, in the near future, will do so directly (through improved building energy management). The impact of energy outsourcing could be very significant on investment in energy efficiency. Finally, while the Internet economy certainly allows higher GDP growth, it seems unlikely that GDP growth in this decade will see an average growth rate equal to that of the past four years.

For all these reasons, *it seems unlikely that the average annual growth rate of U.S. electricity demand in this decade will significantly exceed the 2.2% growth rate we have experienced since 1996.*

[36]Peter Huber and Mark Mills, "Got a Computer? More Power to You," *Wall Street Journal*, September. 7, 2000, p. A 26.

Primary energy demand may be even more important than electricity demand growth, since it determines carbon dioxide emissions. If indeed the Internet is already reducing energy intensity, then it is likely to have a bigger impact in the years to come. The Internet economy in the United States is projected to grow more than ten-fold—from its current level of tens of billions of today to more than $1 trillion in a few years. Moreover, while the Internet economy remains a small share of the total U.S. economy, it represents a much higher fraction of the *growth* in the economy.

The combination of trends described above makes it likely that this decade will not see the same low-level of energy intensity gains that the 1987 to 1996 period saw, which were under 1% per year. Annual reductions of U.S. energy intensity in the Internet era could well average 2.0%. If this comes to pass, most major economic models used in the country will need to be modified. It may be that many factors widely used in economic, energy, and environmental models—such as energy per GDP and inventories per GDP—need to be changed.

Amazingly, EIA has looked at recent trends and while it has boosted its energy intensity predictions, it has apparently concluded that U.S. carbon dioxide emissions growth will actually be higher than previously projected.[37] We believe that many widely-used predictions of growth in energy usage and GHG emissions for this decade, particularly EIA's, are probably high.

The Environmental Protection Agency did a preliminary analysis of potential impact of structural and economic changes driven by rapid growth in the IT-producing industries. The results suggest that mainstream forecasts, such as those by EIA, may be overestimating U.S. energy use in the year 2010 by as much as 5 quadrillion BTUs, wrongly inflating carbon dioxide emissions by up to 300 million metric tons. This equals about 5% of the nation's projected energy use and GHG emissions.

Conclusion

Contrary to a very popular myth fostered by the work of Mark Mills and Peter Huber, the Internet is not driving an acceleration of electricity demand. It appears instead to be driving efficiencies throughout the economy that have resulted in the biggest dropped into electricity intensity and energy intensity the nation has seen in decades.

[37] Personal Communications with Skip Laitner, EPA, September 2000.

Power for a Digital Society

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Once or twice in a century, "enabling sectors" of the economy emerge which are so profound in their impact that they transform *all other* sectors of the economy. There are typically a few key "disruptive" technologies that underpin these enabling sectors and the creation of new economic structures. In this vein, the steam engine and telegraph transformed the 19th century through the creation of new transportation and communication networks. In the 20th century, electricity, by providing more precise and efficient energy, plus practical access to the electromagnetic spectrum (e.g., IR, UV, Xray, microwave), transformed every aspect of society. For this reason, the National Academy of Engineering recently voted the "vast networks of electrification" as the greatest engineering achievement of the 20th century.

Now, we are facing another transformative era. In the 21st century, the information networks relying upon integrated circuits (microprocessors) powered by electricity and linked by high-speed, broadband communication are envisioned to have a comparable, transformative role in creating the Digital Society. This technology revolution has progressed through three stages, each one more significant in its impact on society. The first stage began with computers, which revolutionized information processing and fundamentally transformed the way most businesses operate. The second followed as the cost of microprocessing capability plunged, and individual silicon chips began to appear in all sorts of unexpected places—from phones to car brakes. This embedded-processor phase of digitization has progressed to the point where today, for every chip *inside* a computer, there are 30 more in stand-alone applications.

The third phase involves linking these computers and microprocessors together into networks that allow economies of scale to grow exponentially. There are currently more than a million Web sites available on the Internet, potentially

[1]Note that the contents present the views of their authors, not necessarily those of the Department of Energy, RAND, or any other organization with which the authors may be affiliated.

available to some 300 million computers around the world. As a result, Internet-based commerce already represents about 2% of the American GDP, and by the end of next year the revenues from e-commerce are expected to exceed those of the entire U.S. electric power industry. Increasingly, stand-alone microprocessors are being linked to networks, supplying critical information on equipment operations and facilitating even more profound changes in daily life.

Electricity Requirements in the Digital Society

Together, microprocessors and the equipment they control have helped stimulate growth in the demand for electricity well beyond previous expectations. Information technology is the fastest growing market for electricity and now accounts for 10-13% of the electrical energy consumed in the U.S.

- Given the growth in the Internet's direct and indirect usage of electricity, the equivalent of 30%-50% of today's US power production may be needed to serve the needs of the booming digital society within the next decade or two.
- Power demand in Silicon Valley is indicative of the future of the digital society. For example, total demand growth in the valley is currently running at about 5%/year, much of it due to high-tech expansion. This is more than twice the national average. It is quickly absorbing capacity margins for both generation and power delivery are racing well ahead of capital spending by utilities.
- This demand growth is coming primarily from new end-users; particularly data centers and co-location facility providers, data storage providers, cellular, PCS and radio tower operators, and the optical components industry.

As recently as the 1970s, electricity accounted for only 25% of the energy consumption in the industrialized nations. By 2000 it had risen to more than 37%. During the next 25 years, electricity is likely to grow to provide more than 50% of the energy consumed in these nations, and even more if electrified transportation takes hold. In doing so, energy efficiency will also continue to grow with less and less energy needed to power the economy.

What is equally important, however, is *how* society will transform its use of electricity in the new millennium. Computers, the Internet, advanced automation, smart houses, critical care equipment, fiber optic communications, digital household appliances, e-commerce companies, wireless phone systems, the list of digital technologies goes on. Appliances and automated processes, linked via telecommunications services, will control energy purchases, metering,

environmental control, lighting, and security, etc. Consumers will use the Internet economy to connect directly with energy markets, while buying and paying via electronic commerce.

This emerging Internet economy depends upon a server and fiber-optic based network whose power demands necessitate an extremely high level of reliability and quality. The growth in Internet-based commerce fundamentally depends on the reliability of its power supply backbone. What is digital-quality power? Realistically speaking, most of the electricity delivered in the US has a reliability of about 99.9% (based on average annual outage duration), with a variety of disturbances which reduce overall quality to something less. That is not good enough for a digital society. Interruptions and disturbances measuring less than one cycle (less than 1/60th of one second) are enough to crash servers, computers, intensive care and life support machines, automated equipment, and other microprocessor-based devices. For example, power disturbances around the world cause more than 17,000 computer disruptions every second, ranging from annoying frozen cursors to serious disruptions of equipment and products.

Proliferation of digital technology raises two challenges for those who must supply the necessary electric power—quality as well as quantity. On an annual basis, that means electricity must be available to the microprocessor at least 99.9999999% of the time—"9-nines reliability" as it's sometimes called. Many of the measures required to achieve 9-nines entail devices that are on the customer's side of the meter, but linked in seamless fashion to the power supply system. Economics is the primary driver.

Information technology companies already are taking steps to ensure their own supply of ultra high-quality electrical power. Oracle Corp., for example, has built their own substation, pointing out that their power costs could triple and not impact their product cost, whereas an outage carries heavy and growing costs. An Oracle spokesperson brought the point home. "What is self-sufficiency [to ensure power quality] worth to us? Millions of dollars per hour. It is so important that you can't calculate the value to us and our customers."

Another sign of the need for digital-quality power is rapid growth of the power conditioning industry. Bank of America Securities recently issued a report showing the demand for Internet quality power increasing at a compound rate of 17%/year through at least 2010, roughly in line with shipments of high-end servers. Coupled to this is an emerging "energy technology" industry, focused on the use of power conditioning, uninterruptible power systems (UPS) based on battery storage, and distributed power resources that can provide ultra high-quality power for the Internet. This "silicon power plant" industry is expected to

grow from a few billion dollars in sales today to $50 billion/year by 2005, to $100 billion/year by 2010.

Creating the Needed Electrical Infrastructure

The North American bulk electricity delivery system is not keeping pace with the escalating demands of competition, or with the exacting requirements of a rapidly expanding digital society. For example, over the past decade, electricity demand in the US has grown by roughly 30% while additional transmission capacity has only grown by 15%. In the next decade, US demand is expected to grow by 20%, while planned transmission system growth is expected to be only 3.5%. If the bulk power delivery system cannot dependably supply the so-called "silicon power plants," which raise the reliability level of bulk power to the digital level of reliability and quality, then it will be displaced as the primary energy supplier for the digital society.

The power delivery infrastructure is already a complex, interactive network. But if it is to keep pace with the digital revolution, it too must become much more interactive and complex. Today's infrastructure, composed of relatively few large power plant nodes and limited real-time connectivity, must expand to provide greater precision and efficiency to meet the needs of the microchip networks it serves. In terms of energy supply, the emerging infrastructure requires the incorporation of smaller stationary and mobile distributed power supply and storage nodes. For example, five truck-mounted diesel generators have just been approved for use in meeting peak demand in the San Francisco Bay area next summer. This will result in a more nearly seamless electricity/natural gas network infrastructure with power available at a myriad of locations. It is paradoxical that the very electricity industry that made others obsolete (e.g.. gas light and ice refrigeration) in the 20th century, is itself threatened by a new wave of disruptive technological change as we enter the 21st century.

In the digital economy there will also be a new level of customer involvement in energy markets. This new concept engages customers directly with Internet-based information on energy availability, prices, and assets. The digital information economy enables all players in the market to be tied together through instantaneous and ubiquitous communication, forming a dynamic network, opening up the possibility for new and more creative relationships between buyers and sellers.

A three-step, electricity infrastructure transformation is thus envisioned:

1. The first order of business is to keep the lights on.

2. The second is to use existing technology to upgrade the power delivery system to handle the new volume and patterns of traffic created by wholesale and retail electricity competition.
3. The third is to begin the process of transformation of the entire power system so that all elements, from generation to end-use, form the equivalent of an integrated circuit, able to respond at the speed of light while retaining the necessary levels of power stability in all parts of the system.

The high-power electronics needed to complete this transformation are about 20 years behind micro-circuitry but are now becoming available (e.g., solid state transfer switches, FACTS, custom power, etc.). The research goals are to drive down the capital costs of these high-power electronics, to saturate the entire system with low-cost sensors and feedback loops, and to develop the wide-area management systems for continental-scale integration and control.

A similar, synergistic technology transformation opened up the telecommunications business. For example, microwave transmission enabled new companies to build long distance telephone networks. This was followed by digital switching that allowed telephone companies to offer new services, and to process the information needed to coordinate traffic from different service providers. Next, fiber optics enabled competitive local networks, while wireless enabled users to bypass traditional services. Most recently, the Internet offers all the conventional communications capabilities plus more, and it is leading to unlimited real-time connectivity and plunging transaction costs.

From the standpoint of technology, business and policy alike, the telecommunications transformation is stimulating a corresponding transformation in electricity service. Digitalization of all forms of communication is also driving convergence among the networked utility industries. Conversely, the emergence of full-fledged wholesale and retail power wheeling will require enormous amounts of data to be captured, processed, and made available to buyers and sellers of power, thus placing new demands on telecommunications.

Infrastructure Convergence

Four forces are creating convergence among diverse utility services: digital information technology, energy utility economics, deregulation, and consumer demand.

- In the near-term, for example, this means that electricity and gas services may merge aspects of common infrastructure, including operations,

maintenance, customer service, and billing. Further in the future, communications technologies may be added to this mix.

- Ultimately, the converged utility infrastructure may, in turn, help facilitate other urban services, such as high-speed transportation networks.

This trend toward convergence was recognized recently by a forum of the Consumer Energy Council of America, which stated:

> The potential of a nationwide broadband network and all of its advanced capabilities will be bringing together some of the largest communication concerns in the world as telephone, cable, satellite and wireless converge to transform the information superhighway into a high-speed communications vehicle delivering advanced Internet applications. For those who have access to the network, broadband technology promises to drastically alter and enhance the way people live their lives and how the nation's business is conducted.

Similarly, the Morgan Stanley Dean Witter Global Electricity Team has concluded:

> In our view, a natural union exists between electric utilities and telecom industries due to electrics' existing infrastructure, primarily related to their rights of way (ROW) and internal communication systems.... Specifically, by using these assets, the utilities' average network construction costs are 14% below those of new entrants and 58% below private market purchases of ROW access. Achieving even a 0.1% share of the long-haul telecom market would increase annual revenue by $100 million.

In the digital society, consumers will likely purchase energy as part of an integrated service package. Currently, consumers have an electric meter, a gas meter and pay for gasoline at a metered pump. In the future, consumers will be able to pay for all energy and other essential community services with a single identification number, regardless of the point source of the energy or resource. Delivery of power and information (telecommunications) will become completely interwoven. Finally, just as telecommunications are delivered in a two-way setting, power will increasingly be delivered two-way, as households and industrial enterprises are increasingly able to sell power back to the grid.

Technology Considerations

Technology is central to the successful development of an electrical infrastructure to support a digital society. Its primary role is to ensure that the underlying infrastructure itself does not become the limiting factor in the growth of the

network economy. Electricity is arguably the most critical of the infrastructures because it is the lifeblood of all other systems. However, in the broadest sense, technology needs will be driven by distinct reliability goals for power transmission and for power distribution. Clearly the solution will involve a combination of options: *Simply "gold plating" the present power delivery system would not be an effective, way* to provide high-reliability power for the digital economy. Rather, four distinct infrastructure reliability goals need to be considered:

1. Improvements in high-voltage transmission networks need to focus on increasing capacity and enhancing reliability enough to support a stable wholesale power market. Specifically, new technologies need to be deployed that can prevent cascading outages and price spikes like those that have occurred recently. Such infrastructure improvements will ensure that the U.S. transmission grid can provide lowest-cost power evenly across wide regions of the country.
2. Improvements in utility distribution systems need to focus on integrating low-cost power from the transmission system with an increasing number of local generation and storage options—collectively known as distributed resources (DR)—which will play a vital role in providing high reliability retail electricity, whether deployed by power providers or by customers themselves. It is likely that an increasing amount of Internet power will be delivered on-site, as well as uninterruptible power supply (UPS) systems incorporating storage and DR.
3. The very character of digitally based electric energy devices and appliances must be subject to more standardization as to their installation, compatibility, and sensitivity to reliability and other distortions in electricity. For example, lack of electromagnetic compatibility causes wireless radiated power quality disturbances that increasingly lead to improper operation of industrial control devices. Furthermore, adequate guidelines, let alone standards, do not exist for even wiring a digital infrastructure-ready building.
4. Net metering (buying and selling power through an "smart" electronic meter) and real-time pricing must also be encouraged to facilitate price-signals and demand-response in the retail electricity market. Lacking such advances, there is no economic incentive for customers to conserve at times of high demand (and high generation cost) or to sell electricity back to the utility from distributed generation sources.

Meeting these goals will require adoption of separate strategies for improving the reliability of transmission and distribution systems as well as the

performance of end-use devices. Both sets of strategies rely heavily on the use of new technology, but important choices must still be made about how best to apply these technologies to meet reliability and economic goals.

First Steps Toward Meeting the Need

EPRI is responding to this need by launching a bold, two-phase plan aimed at mobilizing all stakeholders in a unified endeavor to improve overall power system reliability—from generator to end-user—in the most cost-effective manner. The first phase of the plan, called the Power Delivery Reliability Initiative, is well underway and has focused on making immediate, clearly needed improvements in utility transmission and distribution systems. Already, the Initiative has supplied new tools to transmission system operators to help avoid the spread of regional disturbances, and distribution system owners are benefiting from identification of common problems that can contribute to local outages.

The second phase will commence early in 2001 with formation of the Consortium for Electric Infrastructure to Support a Digital Society (CEIDS), a broadly based effort to find long-term solutions to the challenges of reliability. Specifically, CEIDS will focus on three reliability goals:

1. Preparing high-voltage transmission networks to have the increased capacity and enhanced reliability needed to support a stable wholesale power market.
2. Determining how distribution systems can best integrate low-cost power from the transmission system with an increasing number of local generation and storage options.
3. Analyzing ways to provide digital equipment, such as computers, with an appropriate level of built-in protection.

EPRI has pioneered many of the advanced technologies that are now being considered for widespread deployment on transmission and distribution networks and in end-use devices as a way to increase overall system reliability. By promoting judicious use of these technologies, CEIDS can make a significant contribution to electric reliability in ways that could potentially contribute billions of dollars in increased productivity to the American economy.

With this in mind, the authors believe that DOE should join EPRI in supporting this public/private consortium, to develop the technologies necessary to support the electric reliability needs of a rapidly expanding digital society. Specifically, EPRI hopes to fund CEIDS by raising $20 million a year for four years from

utility sources and high-tech companies concerned about the future of electric power reliability. Matching funds from DOE could provide the support needed to make CEIDS a truly national effort—an important public-private consortium addressing one of the most critical energy issues of our time.

Conference Papers on Worker Productivity, Building Design, and Energy Use

Health and Productivity Gains from Better Indoor Environments and Their Implications for the U.S. Department of Energy

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A substantial portion of the U.S. population suffers frequently from communicable respiratory illnesses, allergy and asthma symptoms, and sick building syndrome symptoms. We now have increasingly strong evidence that changes in building design, operation, and maintenance can significantly reduce these illnesses. Decreasing the prevalence or severity of these health effects would lead to lower health care costs, reduced sick leave, and shorter periods of illness-impaired work performance, resulting in annual economic benefits for the U.S. in the tens of billions of dollars. Increasing the awareness of these potential health and economic gains, combined with other factors, could help bring about a shift in the way we design, construct, operate, and occupy buildings. The current goal of providing marginally adequate indoor environments could be replaced by the goal of providing indoor environments that maximize the health, satisfaction, and performance of building occupants. Through research and technology transfer, DOE and its contractors are well positioned to help stimulate this shift in practice and, consequently, improve the health and economic well-being of the U.S. population. Additionally, DOE's energy-efficiency interests would be best served by a program that prepares for the potential shift, specifically by identifying and promoting the most energy-efficient methods of improving the indoor environment. The associated research and technology transfer topics of particular relevance to DOE are identified and discussed.

[1]Note that the contents present the views of their authors, not necessarily those of the Department of Energy, RAND, or any other organization with which the authors may be affiliated.

Introduction and Objective

Analyses by Fisk and Rosenfeld (1997) provided the first broad review in the U.S. of the potential to improve both health and productivity through improvements in indoor environments. Subsequent papers (Fisk 2000a, 2000b) have upgraded and updated the analyses. This paper summarizes these prior analyses of the potential improvements in health and associated economic benefits, incorporates a few updates, and discusses the implications for the research and technology transfer programs of the U.S. Department of Energy (DOE). The motivation for this effort is to provide input for strategic planning underway by the DOE. Unlike our prior analyses, this paper does not consider opportunities to directly enhance work performance, through changes in the indoor environment, without an associated improvement in health. The potential to directly enhance productivity will be addressed at this conference in other papers.

Underlying the analyses presented in this paper are three pathways to health-related economic benefits, as illustrated in Figure 1. In all cases, the starting point is a change in building design, operation, and maintenance that improves indoor environmental quality (IEQ) and enhances the health of the building's occupants. Economic benefits may result from: (1) reduced health care costs; (2) reduced sick leave; and (3) a reduction in time when health effects diminish the performance of workers while they are at work. The changes in building design, operation, and maintenance undertaken to improve IEQ may increase or decrease building energy use.

Methods

The basic approach was to review the relevant literature and analyze the key studies showing linkages between indoor environmental factors and health outcomes. Relevant papers were identified through computer-based literature searches, reviews of conference proceedings, and discussions with researchers. Communicable respiratory illnesses, allergies and asthma, and sick building syndrome symptoms were identified as the three categories of health effects in the analyses because their prevalences are influenced by IEQ and the affected populations are very large. Published health studies were reviewed to determine the strength of associations between building-related risk factors (e.g., low ventilation rates) and health outcomes. Expertise in building science and engineering provided information on the potential to diminish the risk factors. With these inputs, plus judgments, the potential reductions in health effects were estimated. The economic costs of these adverse health effects were estimated, primarily by synthesizing and updating the results of previously

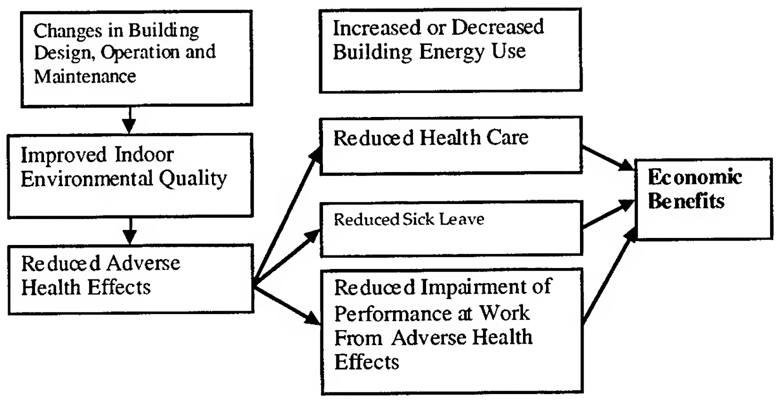

Figure 1—Pathways to Health and Economic Gains

published cost estimates. Prior economic estimates were updated to 1996 to account for general inflation, health care inflation, and increases in population (U.S. Department of Commerce 1997). Finally, the potential annual nationwide health and productivity gains were computed by multiplying the population affected and associated costs by the estimated potential percentage reduction in health effects.

Even with the best of the information currently available, there is a high level of uncertainty with these estimates of the health and associated economic gains attainable from improvements in the indoor environment. In general, the largest source of uncertainty is the degree to which health effects could be reduced through practical changes in building design, operation, and maintenance. A range of estimated gains are provided to reflect this source of uncertainty. For sick building syndrome symptoms, the total costs to society are also uncertain; however, the estimates provided here do not reflect this additional level of uncertainty.

Improvements in the indoor environment depend on changes to building design, operation, maintenance, use, or occupancy. This paper considers whether feasible and practical changes could improve health; however, it does not claim that it will be easy to stimulate the investments or changes in behaviors that are necessary in order to improve IEQ. For example, this paper assumes that it is feasible and practical to restrict indoor tobacco smoking, maintain pets outside of the homes of pet allergic people, improve air filtration systems, prevent low ventilation rates, and reduce water leakage from outdoors to indoors. Realization of the "potential" health and productivity gains identified in this paper will

depend on changes in behavior and, in some cases, on financial investments in better building design, operation and maintenance. The expected benefit-to-cost ratios for these measures will often be large because the salaries and benefits of workers typically dominate building energy, maintenance, and lease costs (Woods 1989).

To make this article understandable to a broad audience, the use of potentially unfamiliar statistical terminology has been minimized. For example, as substitutes for the odds ratios or relative risks normally provided in the scientific literature, this article provides estimates of the percentage increases and decreases in outcomes (e.g., health effects) that are expected when building-related risk factors (e.g., mold exposures) are present or absent. Measures of statistical significance are included only within footnotes. The findings reported in this paper would generally be considered to be statistically significant (e.g., the probability that the findings are due to chance or coincidence is generally less than 5%). Appendix 1 of Fisk (2000b) defines the odds ratio, the relative risk, the term "adjusted", and the means of estimating percentage changes in outcomes from odds ratios or relative risks.

After estimating of potential health and productivity gains, this paper discusses their implication for the US Department of Energy. This discussion is based on the author's knowledge of the interrelationships among building energy efficiency, IEQ, and health and on his understanding of DOE's mission and capabilities.

Potential Health and Productivity Gains

For each of the three health categories, the subsequent text starts with a review of the evidence for the linkage between indoor environmental conditions and the health outcomes, follows with a discussion of the populations affected and associated costs, and concludes with estimates of the potential health and productivity gains.

Communicable Respiratory Illness

Evidence of Linkage. We first consider communicable respiratory illnesses transmitted between people, such as influenza and common colds. Building characteristics could change the number of aerosols containing virus or bacteria, e.g., droplet nuclei from coughs and sneezes, that are inhaled, increase or diminish the viability of the inhaled virus or bacteria, or modify the susceptibility of occupants to infection. Consequently, the following building characteristics

may theoretically affect the prevalences of respiratory illnesses: efficiency or rate of air filtration; rate of ventilation (i.e., supply of outside air per occupant); amount of air recirculation in ventilation systems, separation between individuals (dependent on occupant density and use of private work spaces); air temperature and humidity (which affect the period of viability of infectious aerosols); and mold levels since molds may increase susceptibility to illness. As discussed in Fisk (2000a), infectious aerosols are thought or known to contribute substantially to transmission of common colds (e.g., rhinovirus infections), influenza, adenovirus infections, measles, and other common respiratory illnesses. Disease transmission due to direct person-to-person contact or to indirect contact via contaminated objects, may be largely unaffected by indoor environmental and building characteristics.

In addition to the theoretical expectations, data are available from several field studies that have examined the association of building characteristics with the prevalence of respiratory illness among building occupants. Two studies were performed in military barracks. A large multi-year investigation by the U.S. Army (Brundage et al. 1988) determined that clinically-confirmed rates of acute respiratory illness with fever were 50% higher among recruits housed in newer barracks with closed windows, low rates of outside air supply, and extensive air recirculation compared to recruits in older barracks with frequently open windows, more outside air, and less recirculation.[2] In another barracks study, Langmuir et al. (1948) compared the rate of respiratory illness with fever among recruits housed in barracks with ultraviolet lights (UV) that irradiated the indoor air near the ceiling (a technology designed to kill infectious bioaerosols) to the rate of respiratory illness among recruits in barracks without UV lights. For the entire study period, the population housed in barracks with UV irradiated air had 23% less respiratory illness.[3]

Several additional studies from a variety of building types provide relevant information on this topic. Jaakkola et al. (1993), found that office workers with one or more roommates were about 20% more likely to have more than two cases of the common cold during the previous year than office workers with no roommates.[4] At an Antarctic station, the incidence of respiratory illness was twice as high in the population housed in smaller (presumably more densely populated) living units (Warshauer et al. 1989). In an older study of New York schools (N.Y. State Commission on Ventilation 1923), there were 70% more

[2]Adjusted relative risk = 1.51, 95% confidence interval (CI) 1.46 to 1.56.

[3]No test of statistical significance was performed.

[4]Adjusted odds ratio = 1.35 (95% CI 1.00 - 1.82).

respiratory illnesses[5] and 18% more absences from illness[6] in fan-ventilated classrooms compared to window-ventilated classrooms, despite a lower occupant density in the fan-ventilated rooms. Unfortunately, ventilation rates were not measured in the classrooms. Another study investigated symptoms associated with infectious illness among 2598 combat troops stationed in Saudi Arabia during the Gulf War (Richards et al. 1993). The study results suggest that the type of housing (air-conditioned buildings, non-air-conditioned buildings, open warehouses, and tents) influenced the prevalence of symptoms associated with respiratory illness. Housing in air-conditioned buildings (ever versus never housed in an air-conditioned building while in Saudi Arabia) was associated with approximately a 37% greater prevalence of sore throat[7] and a 19% greater prevalence of cough.[8]

Although jails are not representative of other buildings because of severe crowding and residents that are not representative of the general public, disease transmission in jails is an important public health issue and indoor-environmental factors that influence disease transmission in jails may also be important, but less easily recognized, in other environments. Hoge et al. (1994) studied an epidemic of pneumococcal disease in a Houston jail. There were significantly fewer cases of disease among inmates with 7.4 m2 or more of space[9] relative to inmates with less space. The disease attack rate was about 95% higher in the types of jail cells with the highest carbon dioxide concentrations, i.e., the lowest volume of outside air supply per person.[10]

Drinka et al. (1996) studied an outbreak of influenza in four nursing homes located on a single campus. Influenza, confirmed by analyses of nasopharyngeal and throat swab samples, was isolated in 2% of the residents of Building A versus an average of 13% in the other three buildings[11] (16%, 9%, and 14% in Buildings B, C and D, respectively). After correction for the higher proportion of respiratory illnesses that were not cultured in Building A, an estimated 3% of the residents of Building A had influenza, a rate 76% lower than observed in the other buildings.[12] The total number of respiratory illnesses (i.e., influenza plus other respiratory illnesses) per resident was also 50% lower in Building A.

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[5]Difference more than three times probable error.

[6]Difference greater than probable error.

[7]Adjusted odds ratio =1.57 (95% CI 1.32-1.88).

[8]Adjusted odds ratio = 1.33 (95% CI 1.01 - 1.46)

[9]$p=0.03$

[10]Relative risk = 1.95 (95% CI 1.08-3.48).

[11]$p < 0.001$, Cochran-Mantel-Haenszel statistics

[12]$p < 0.001$, chi-square

Vaccination rates and levels of nursing care did not differ among the buildings. The authors suggested that architectural factors were the cause of the lower infection rate in Building A. The ventilation system of Building A supplied 100% outside air to the building (eliminating mechanical recirculation) while the ventilation systems of the other buildings provided 30% or 70% recirculated air. The Building A ventilation system also had additional air filters. Finally, the public areas of Building A were larger (per resident), reducing crowding that may facilitate disease transmission.

Milton et al. (2000) studied the association of the rate of outside air supply with the rate of absence from work caused by illness in 3720 workers located in 40 buildings with a total of 110 independently-ventilated floors. While absence is not synonymous with respiratory disease, a substantial proportion of short-term absence from work caused by illness results from acute respiratory illness. Ventilation rates were estimated based on ventilation system design, occupancy, and selected end-of-day carbon-dioxide measurements, and buildings were classified as moderate ventilation (~ 12 L s-1 per occupant) or high ventilation (~24 L s-1 per occupant). The absence rate, controlling for age, gender, seniority, crowding, and type of workspace was 35% lower in the high-ventilation buildings.

The association of mold problems in buildings with the incidence of respiratory infections has been investigated in a few studies. One study (Husman et al. 1993, Husman 1996) compared the rates of acute respiratory infection in 158 residents of apartments with verified mold problems to the rates of infection in 139 residents of apartments without mold problems. Approximately twice as many residents of the moldy apartments reported at least one acute respiratory infection during the previous year.[13] A complex multi-stage study examined the association of high mold exposures within day-care centers with common colds as well as other health outcomes in children (Koskinen et al. 1995, 1997) with inconclusive results (i.e., one comparison suggests that mold significantly increased serious persistent respiratory infections while other comparisons found small statistically insignificant decreases in common colds with higher mold exposure.) The recent evidence that mold exposures may adversely affect immune system function (Dales et al. 1998) is consistent with the findings of a positive association between molds and respiratory infections.

Population Affected and Cost of Communicable Respiratory Illness. Virtually everyone is affected by communicable respiratory illnesses. Averaging data from

[13]Relative risk is 2.2, 95% CI is 1.2 to 4.4, adjusted for age, sex, smoking and atopy

1992 through 1994, the civilian non-institutional population experienced 43.3 common colds and 25.7 cases of influenza per 100 population (US Department of Commerce 1997), for a total of 0.69 illnesses per person per year.

The obvious costs of respiratory illness include health care expenses and the costs of absence from work. Additionally, respiratory illnesses may cause a performance decrement at work. In controlled experiments, Smith (1990) has shown that viral respiratory illnesses, even sub-clinical infections, can adversely affect performance on several computerized and paper-based tests that simulate work activities. The decrement in performance can start before the onset of symptoms and persist after symptoms are no longer evident.

Estimates of the productivity losses associated with respiratory illness are based on periods of absence from work and restricted activity days as defined in the National Health Interview Survey (U.S. Department of Health and Human Services 1994). In the U.S., four common respiratory illnesses (common cold, influenza, pneumonia, and bronchitis) cause about 176 million days lost from work and an additional 121 million work days of substantially restricted activity (Dixon 1985, adjusted for population gain). Assuming a 100% and 25% decrease in productivity on lost-work and restricted-activity days, respectively, and a $39,200 average annual compensation (U.S. Department of Commerce 1997), the annual value of lost work is approximately $34 billion.[14] The annual health care costs for upper and lower respiratory tract infections total about $36 billion (Dixon 1985, adjusted for population gain and health care inflation). Thus, the total annual cost of respiratory infections is approximately $70 billion. Neglected costs include the economic value of reduced housework and of absence from school.

Potential Savings. Without being able to substantially change the building-related factors that influence disease transmission, we cannot realize these health care cost savings and productivity gains. A number of existing, relatively practical building technologies, such as increased ventilation, reduced air recirculation, improved filtration, ultraviolet disinfection of air, and reduced space sharing (e.g., shared office), and reduced occupant density have the theoretical potential of reducing inhalation exposures to infectious aerosols by more than a factor of two.

The studies cited above suggest that changes in building characteristics and ventilation could reduce indexes of respiratory illness by 15% (absence from school) to 76% (influenza in nursing homes), with the strongest study (Brundage

[14]A similar estimate, $39 billion, is obtained based on the information in Garabaldi (1985)

et al. 1988) suggesting that a 33% reduction is possible. The amount of time spent in a building should influence the probability of disease transmission within the building. If efforts to reduce disease transmission were implemented primarily in commercial and institutional buildings[15] that people occupy approximately 25% of the time, smaller reductions in respiratory illness would be expected in the general population than indicated by the building-specific studies. To adjust the reported decreases in respiratory illness for time spent in buildings, we estimated the percentage of time that occupants spend in each type of building (100% of time in jails and nursing home, 66% in barracks and housing, and 25% in offices and schools) and assumed that the magnitude of the influence of a building factor on the incidence of respiratory illness varies linearly with time spent in the building. After this adjustment and neglecting the Gulf War study involving some housing in tents and warehouses, the nine remaining studies cited above yield 11 estimates of potential decreases in metrics for respiratory illness (some studies had multiple outcomes such as influenza and total respiratory infections), ranging from 9% to 41% with an average of 19% (see Figure 2). Considering only the studies with explicit respiratory illness outcomes

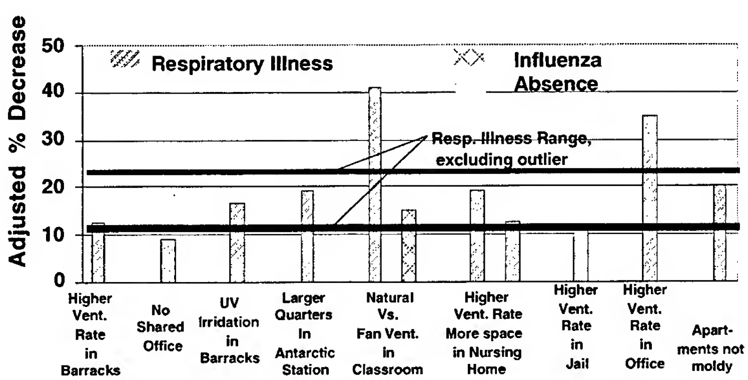

Figure 2. Estimated decreases in respiratory illness from changes in building characteristics.

Figure 2—Estimated Decreases in Respiratory Illness from Changes in Building Characteristics

[15]There are no technical barriers to implementation of similar measures in residences; however, business owners will have a stronger financial incentive to take action than home owners.

(i.e., excluding the study with an absence outcome) results in nine estimates of decreases in respiratory illness, adjusted for time in building, ranging from 9% to 41% with an average of 18%. The range is 9% to 20%, if the outlier value of 41% (illness in schools) is excluded. This narrower range is adopted, i.e., 9% to 20%, for the potential reduction in respiratory illness. With this estimate and 0.69 cases of common colds and influenza per person per year), approximately, 16 to 37 million cases of common cold or influenza would be avoided each year in the US. The corresponding range in the annual economic benefit is $6 billion to $14 billion.

Allergies and Asthma

Linkage. Symptoms of allergies and of asthma may be triggered by a number of allergens in indoor air including those from house dust mites, pets, fungi, insects, and pollens (Committee on Health Effects of Indoor Allergens 1993). Allergens are considered a primary cause of the inflammation that underlies asthma (Platts-Mills 1994). There is evidence (e.g., Arshad et al. 1992, Wahn et al. 1997) that lower exposures to allergens during infancy or childhood can reduce the sensitization to allergens. Asthma symptoms may also be evoked by irritating chemicals, including environmental tobacco smoke (Evans et al. 1987). Viral infections, which may be influenced by building factors, also appear to be strongly linked to exacerbations of asthma, at least in school children. A recent study of 108 children, age 9 to 11, found a strong association of viral infections with asthma exacerbation (Johnston et al. 1995). Viral infections were detected in 80% to 85% of asthmatic children during periods of asthma exacerbation. During periods without exacerbation of asthma symptoms, only 12% of the children had detectable viral infections.[16]

Building factors most consistently and strongly associated with asthma and allergic respiratory symptoms include moisture problems, indoor tobacco smoking, house dust mites, molds, cats and dogs, and cockroach infestation (Committee on the Assessment of Asthma and Indoor Air 1999, Committee on Health Effects of Indoor Allergens 1993). Platts-Mills and Chapman (1987) provide a detailed review of the substantial role of dust mites in allergic disease. In a recent review of the association of asthma with indoor air quality by the National Academy of Sciences (Committee on the Assessment of Asthma and Indoor Air 1999), the prevalence of asthma or related respiratory symptoms is increased by approximately a factor of two[17] among occupants of homes or

[16]The difference between infection rates is statistically significant, $p < 0.001$

[17]Neglecting one study in the review with a very high odds ratio of 16.

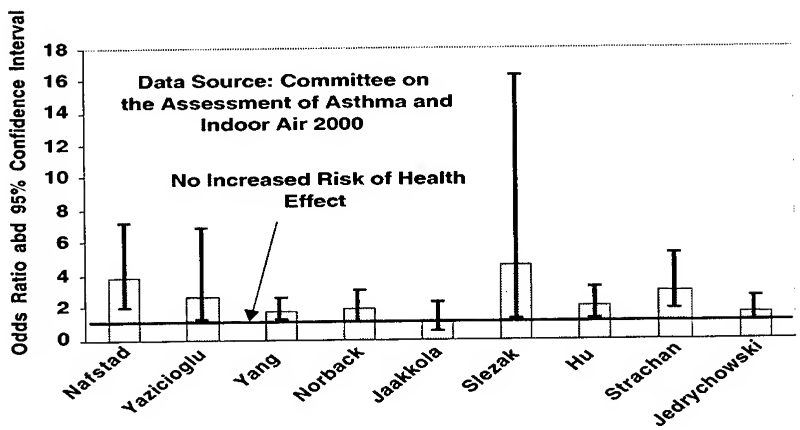

Figure 3. Association of Asthma-Related Health Effects with Dampness Problems or Visible Molds

schools with evidence of dampness problems or molds (Figure 3). In the same review, environmental tobacco smoke exposure, indicated by parental smoking, is typically associated with increases in asthma symptoms or incidence by 20% to 40%.

Data from few office-based studies are available for asthma and allergy associations with indoor environmental conditions. In case studies, moisture and related microbiological problems have been linked to respiratory symptoms in office workers (Division of Respiratory Disease Studies 1984, Hoffmann et al. 1993). In a study of office workers[18] (Menzies et al. 1988), higher relative humidity, higher concentrations of alternaria (a mold) allergen in air, and higher dust mite antigen in floor dust were associated with a higher prevalence of respiratory symptoms.

Overall, the evidence of a linkage between the quality of the indoor environment and the incidence of allergic and asthma symptoms is strong. Additionally, the exposures that cause allergic sensitization often occur early in life and are likely to occur indoors; consequently, the quality of indoor environments may also influence the proportion of the population that is allergic or asthmatic.

Population Affected and Cost of Allergies and Asthma. Approximately 20% of the U.S. population have allergies to environmental antigens (Committee on Health Effects of Indoor Allergens 1993) and approximately 6% have asthma

[18]This was a case-control study of ~ 17% of all workers in the buildings.

(Rappaport and Boodram 1998). Drawing upon five recent papers, Fisk (2000b) has estimated that the annual costs for 1996 of allergies and asthma in the U.S. is $15 billion. Approximately $10 billion are health care costs and the remaining costs are indirect costs, for example the costs of lost work and school. A significant portion of the costs of allergies and asthma reflect the burden of these diseases in children.

Potential Savings from Changes in Building Factors. There are three general approaches for reducing allergy and asthma symptoms via changes in buildings and indoor environments. First, one can control the indoor sources of the agents that cause symptoms (or that cause initial allergic sensitization). For example, indoor tobacco smoking can be restricted to isolated separately-ventilated rooms, or prohibited entirely. Pets can be maintained outside of the homes of individuals that react to pet allergens. Perhaps even more broadly effective are measures that reduce the growth of microorganisms indoors. Changes in building design, construction, operation, and maintenance could reduce water leaks and moisture problems and decrease indoor humidities (where humidities are normally high), leading to a reduction in dust mites and molds in buildings. Known reservoirs for allergens, such as carpets for dust mite allergen, can be eliminated or modified. Improved cleaning of building interiors and HVAC systems can also limit the growth or accumulation of allergens indoors. There are no major technical obstacles to these measures.

The second general approach for reducing allergy and asthma symptoms is to use air cleaning systems or increased ventilation to decrease the indoor airborne concentrations of the relevant pollutants. Many of the relevant exposures are airborne particles. Technologies are readily available for reducing indoor concentrations of airborne particles generated indoors. Better filtration of the outside air entering mechanically-ventilated buildings can also diminish the entry of outdoor allergens into buildings. Filtration is likely to be most effective for the smaller particles linked to allergies and asthma, such particles from tobacco smoke. Allergens that are large particles, e.g., from dust mites, have high gravitational settling velocities and are less effectively controlled by air filtration.

The influence of particle air cleaners on symptoms of allergies and asthma is reviewed by Committee on the Assessment of Asthma and Indoor Air (1999), and one more recent study is provided by van der Heide (1999). Many published studies have important limitations such as small air cleaners, a small number of subjects, or a focus on dust mite allergies which may be poorly controlled with air cleaners due to the large size and high settling velocities of dust mite allergens. Five of twelve studies involving subjects with perennial allergic disease or asthma reported statistically significant improvements in symptoms or

airway hyperresponsiveness, or reduced use of medication when air cleaners were used. In six of seven studies, seasonal allergic or asthma symptoms were significantly reduced with air cleaner use. Subjects were blinded, i.e., unaware of air cleaner operation, in only two of these studies involving seasonal symptoms; thus, results could have been biased by the subjects' expectations.

Because viral respiratory infections will often exacerbate asthma symptoms, a third approach for reducing asthma symptoms is to modify buildings in a manner that reduce viral respiratory infections among occupants, as discussed previously.

With the available data, the magnitude of the potential reduction in allergy and asthma symptoms is quite uncertain, but some reduction is clearly possible using practical measures. The subsequent estimate is based on two considerations: 1) the degree to which indoor allergen concentrations and concentrations of irritating chemicals can be reduced, and 2) the strength of the reported associations between symptoms and changeable building and IEQ factors. Regarding the first consideration, significant reductions in allergy and asthma symptoms would not be expected unless it was possible to substantially reduce indoor concentrations of the associated allergens and irritants. From engineering considerations, it is clear that concentrations of many allergens could be reduced very substantially. Filtration systems, appropriately sized, should be capable of reducing concentrations of the smaller airborne allergens by approximately 75%. Some of the source control measures, such as elimination of water leaks, control of indoor humidities, reduction or elimination of indoor smoking and pets, and improved cleaning and maintenance are likely to result in much larger reductions in the pollutants that contribute to allergies and asthma.

As discussed above, several cross-sectional or case-control studies have found that building-related risk factors, such as moisture problems and mold or environmental tobacco smoke, are associated with 20% to 100% increases in allergy and asthma symptoms, implying that 16% to 50% reductions in symptoms are possible by eliminating these risk factors. However, the complete elimination of these risk factors is improbable. Assuming that it is feasible and practical to reduce these risks by a factor of two, leads to a 8% to 25% estimate of the potential reduction in allergy and asthma symptoms. With this estimate, the annual savings would be ~$1 to ~$4 billion. Control measures can be targeted at the homes or offices of susceptible individuals, reducing the societal cost.

Sick Building Syndrome Symptoms

Linkage. Characteristics of buildings and indoor environments have been linked to the prevalence of acute building-related health symptoms, often called sick-building syndrome (SBS) symptoms, experienced by building occupants. SBS symptoms include irritation of eyes, nose, and skin, headache, fatigue, and difficulty breathing. Although psychosocial factors such as job stress influence SBS symptoms, many building factors are also known or suspected to influence these symptoms including: type of ventilation system; rate of outside air ventilation; level of chemical and microbiological pollution; and indoor temperature and humidity (Mendell 1993; Sundell 1994; Menzies and Bourbeau 1997, Seppanen et al. 1999). In the review by Seppanen et al. (1999), 21 of 27 assessments meeting study quality criteria found lower ventilation rates to be significantly associated with an increase in at least one SBS symptom (Figure 4). Extrapolating from one of the largest studies, a 5 L s-1 increase in ventilation rates in US office buildings would reduce the proportion of office workers with frequent upper respiratory symptoms from 26% to 16%. For eye symptoms, the corresponding reduction would be from 22% to 14%. In a set of problem buildings studied by (Sieber et al. 1996), SBS symptoms were associated with evidence of poorer ventilation system maintenance or cleanliness. For example, debris inside the air intake and poor drainage from coil drain pans were associated with a factor of three increase in lower respiratory symptoms.[19] In the same study, daily vacuuming was associated with a 50% decrease in lower respiratory symptoms.[20] In some, but not all, controlled experiments, SBS symptoms have been reduced through practical changes in the environment such as increased ventilation, decreased temperature, and improved cleaning of floors and chairs (Mendell 1993, Menzies and Bourbeau 1997, Seppanen et al. 1999). Therefore, SBS symptoms are clearly linked to features of buildings and indoor environments.

Population Affected and Cost of SBS Symptoms. SBS symptoms are most commonly reported by office workers and teachers that make up about 50% of the total workforce (64 million workers[21]). In a modest fraction of buildings, often referred to as "sick buildings", symptoms become severe or widespread, prompting investigations and remedial actions. The term "sick building

[19]For debris in air intake, relative risk = 3.1 and 95% CI = 1.8 to 5.2 For poor or no drainage from drain pans, relative risk = 3.0 and 95% CI = 1.7 to 5.2

[20]Relative risk = 0.5, 95% CI = 0.3 to 0.9

[21]Based on statistical data of employed civilians by occupation (US Department of Commerce 1997), there are approximately 63 million civilian office workers plus teachers (49.6% of the civilian workforce). Assuming that 50% of the 1.06 million active duty military personnel are also office workers, the total is approximately 63.5 million.

Figure 4. Ventilation rates per person and SBS symptoms. (Data source: Seppanen et al. 1999)

Author	Yr.	Relative risk or (odds ratio)
Jaakkola	91a	1.1
Gamble	86	1.8
Gamble	86	2.4
Groes	95	N/A
Jaakkola	91b	1.3
Jaakkola	91b	1.2
Jaakkola	91b	1.1
Jaakkola	95	5.4-37
Cochet	95	1.7 - 3.8
Sundell	94	(2-3)
Ruotsalainen	94	2.8
Sundell	94a	N/A
Stenberg	94	(1.87)
Wu	96	N/A
Wu	96	N/A
Sundell	94a	N/A
Jaakkola	91a	1.1
Sundell	94b	(1.8)
Jaakkola	95	5.0-6.0
Jaakkola	91a	1.1
Nordström	95a	(1.9-2.6)
Jaakkola	94	0.35-0.46
Jaakkola	91a	N/A
Wyon	92	N/A
Menzies	93a	0.8-1.2
Wyon	92	N/A
Jaakkola	95	4.2-5.2

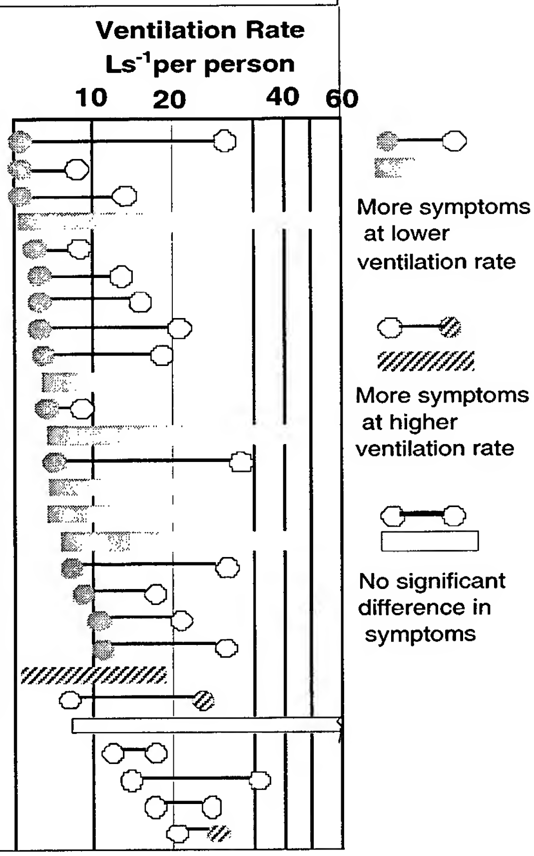

Figure 4—Ventilation Rates per Person and SBS Symptoms

syndrome" is widely used in reference to the health problems in these buildings. However, the syndrome appears to be the visible portion of a broader phenomenon. These same symptoms are experienced by a significant fraction of workers in "normal" office buildings that have no history of widespread complaints or investigations (e.g., Fisk et al. 1993; Nelson et al. 1995, Brightman et al. 1997), although symptom prevalences vary widely among buildings. The most representative data from US buildings, obtained in a 56-building survey (that excluded buildings with prior SBS investigations) found that 23% of office workers reported two or more frequent symptoms that improved when they were away from the workplace. (HS Brightman, Harvard School of Public Health, Personal Communication). Applying this percentage to the estimated

number of U.S. office workers and teachers (64 million), the number of workers frequently affected by at least two SBS symptoms is 15 million.

SBS symptoms are a hindrance to work and are associated with absences from work (Preller et al. 1990) and visits to doctors. When SBS symptoms are particularly disruptive, investigations and maintenance may be required. There are financial costs to support the investigations and considerable effort is typically expended by building management staff, by health and safety personnel and by building engineers. Responses to SBS have included costly changes in the building, such as replacement of carpeting or removal of wall coverings to remove molds, and changes in the building ventilation systems. Some cases of SBS lead to protracted and expensive litigation. Moving employees imposes additional costs and disruptions. Clearly, these responses to SBS impose a significant societal cost, but information is not available to quantify this cost.

Calculations indicate that the costs of small decreases in productivity from SBS symptoms are likely to dominate the total SBS cost. Limited information is available in the literature that provides an indication of the influence of SBS symptoms on worker productivity. In a New England Survey, described in EPA's 1989 report to Congress (U.S. Environmental Protection Agency, 1989), the average self-reported productivity loss due to poor indoor air quality was 3%. Woods et al. (1987) completed a telephone survey of 600 U.S. office workers and 20% of the workers reported that their performance was hampered by indoor air quality, but the study provided no indication of the magnitude of the productivity decrement. In a study of 4373 office workers in the U.K. by Raw et al. (1990), workers who reported higher numbers of SBS symptoms during the past year also indicated that physical conditions at work had an adverse influence on their productivity. Based on the data from this study, the average self-reported productivity decrement for all workers, including those without SBS symptoms, was about 4%.[22] In an experimental study (Menzies et al. 1997b), workers provided with individually-controlled ventilation systems reported fewer SBS symptoms and also reported that indoor air quality at their workstation improved productivity by 11% relative to a 4% decrease in productivity for the control population of workers.[23]

[22]The data indicate a linear relationship between the number of SBS symptoms reported and the self-reported influence of physical conditions on productivity. A unit increase in the number of symptoms (above two symptoms) was associated with approximately a 2% decrease in productivity. Approximately 50% of the workers reported that physical conditions caused a productivity decrease of 10% or greater; 25% of workers reported a productivity decrease of 20% or more. Based on the reported distribution of productivity decrement (and productivity increase) caused by physical conditions at work, the average self-reported productivity decrement is about 4%.

[23]$p < 0.05$ for the reduction in SBS symptoms and $p < 0.001$ for the self-reported change in productivity.

In addition to these self-reported productivity decrements, measured data on the relationship between SBS symptoms and worker performance are provided by Nunes et al. (1993). Workers who reported any SBS symptoms took 7% longer to respond in a computerized neurobehavioral test[24] and error rates in this test decreased non-significantly (the18% decrease was not significant). In a second computerized neurobehavioral test, workers with symptoms had a 30% higher error rate[25] but response times were unchanged. Averaging the percent changes from the four performance outcomes yields a 14% decrement in performance among those with SBS symptoms. Multiplying by the estimated 23% of office workers with 2 or more frequent symptoms yields a 3% average decrease in performance.

Other objective findings were obtained in a study of 35 Norwegian classrooms. Higher concentrations of carbon dioxide, which indicate a lower rate of ventilation, were associated with increases in SBS symptoms and also with poorer performance in a computerized test of reaction time[26] (Myhrvold et al. 1996); however, the percentage change in performance was not specified. Renovations of classrooms with initially poor indoor environments, relative to classrooms without renovations, were associated with reduced SBS symptoms and with improved performance by 5.3% in the reaction time tests[27] (Myhrvold and Olsen 1997).

Investigations by Wargocki et al. (1999, 2000, 2000a) and Lagercrantz et al. (2000) provide additional objective evidence that SBS symptoms reduce productivity. In a series of laboratory-based, blinded, controlled, randomized experimental studies, the health symptoms and satisfaction with of IEQ of workers were monitored along with the workers' performance of work-related tasks including: typing, addition, proof reading, and creative thinking. The laboratory had the appearance of a normal office but enabled precise control of all environmental parameters. Some experiments were performed with and without a pollutant source (a 20 year old carpet) placed in the laboratory behind a visual screen. Other experiments varied the outside air ventilation rate with the carpet present. The study design controlled for the effects on performance of learning when tasks were repeated. These studies have shown that removing the pollutant

[24] $p < 0.001$

[25] $p = 0.07$

[26] Correlation coefficient = 0.11 and P value = 0.009 for performance versus carbon dioxide. Correlation coefficient = 0.20 and P value = 0.000 for performance versus a score for headache, heavy headed, tiredness, difficulty concentrating, and unpleasant odor. Correlation coefficient = 0.11 and P value = 0.008 for performance versus a score for throat irritation, nose irritation, runny nose, fit of coughing, short winded, runny eyes. Correlation coefficients are controlled for age.

[27] Measures of statistical significance are not included in paper.

source (carpet) or increasing ventilation rates with the pollutant source present were associated with increased satisfaction with indoor air quality,[28] decreases in some SBS symptoms,[29] and increases in performance in text typing, proof reading, and addition.[30] Considering these three work tasks, these studies suggest that doubling of the ventilation rates increase overall performance by 1.9% (Wargocki et al. 2000a). Subsequent analyses indicated that the work performance improved only when the intensity of SBS symptoms diminished and identified a 7% improvement in the score on a creative thinking test[31] as the ventilation rates increased from 3 to 10 L s-1 per person (Wargocki et al. 2000b).

The estimate of the productivity loss from SBS symptoms must be based on the limited information available. The self-reports discussed above suggest a productivity decrease, averaged over the entire work population, of approximately 4% due to poor indoor air quality and physical conditions at work. Although SBS symptoms seem to be the most common work-related health concern of office workers, some of this self-reported productivity decrement may be a consequence of factors other than SBS symptoms. Also, dissatisfied workers may have provided exaggerated estimates of productivity decreases. The objective data reviewed above suggest that SBS symptoms are associated with decrements on the order of 2% to 3%. Based on these data, we assume a productivity decrease caused by SBS equal to 2%, recognizing that this estimate is highly uncertain. This 2% estimate is the basis for subsequent economic calculations.

SBS symptoms are primarily associated with office buildings and other non-industrial indoor work places such as schools. According to Traynor et al. (1993), office workers are responsible for approximately 50% of the US annual gross national product. Statistical data on the occupations of the civilian labor force are roughly consistent with this estimate (US Department of Commerce 1997), i.e., 50% of workers have occupations that would normally be considered office work or teaching. Since the gross domestic product (GDP) of the US in 1996 was $7.6 trillion (US Department of Commerce 1997), the GDP associated with office-type work is approximately $3.8 trillion. Multiplying the number of office workers and teachers (64 million) by the annual average compensation for all workers

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[28] For pollutant source removal, $P < 0.001$ and $P = 0.062$ in two studies. For ventilation rate increase $P = 0.010$. (Wargocki et al 2000a)

[29] For pollutant source removal $p < 0.04$ for severe headache in Wargocki (1999), $p < 0.02$ for dizziness in Lagercrantz et al. (2000), $p < 0.04$ for difficulty in thinking clearly in Lagercrantz et al. (2000)

[30] $P = 0.0002$ for text typing, $P = 0.056$ for addition, $P = 0.08$ for proof reading (Wargocki et al 2000a)

[31] $P = 0.046$

($39.2K) results in a roughly similar estimate of $2.5 trillion. Averaging these two estimates yields $3.2 trillion. Based on the estimated 2% decrease in productivity caused by SBS symptoms, the annual nationwide cost of SBS symptoms is on the order of $60 billion.

Potential Savings from Changes in Building Factors. Because multiple factors, including psychosocial factors, contribute to SBS symptoms, we cannot expect to eliminate SBS symptoms and SBS-related costs by improving indoor environments. However, strong evidence cited by Mendell (1993), Sundell (1994), and Seppanen et al. (1999) of associations between SBS symptoms and building environmental factors, together with our knowledge of methods to change building and environmental conditions, indicate that SBS symptoms can be reduced. As discussed, many SBS studies[32] have found individual environmental factors and building characteristics to be associated with changes of about 20% to 50% in the prevalence of individual SBS symptoms or groups of related symptoms.[33] A smaller number of studies have identified a few building-related factors to be associated with an increase in symptoms by a factor of two or three (e.g., Jaakkola and Miettinen 1995, Sieber et al. 1996). The review by Seppanen et al. (1999) suggests that a 5 L s-1 per person increase in building ventilation rates in the building stock would decrease prevalences of upper respiratory and eye symptoms by ~35%.

In summary, the existing evidence suggests that substantial reductions in SBS symptoms, on the order of 20% to 50%, should be possible through improvement in individual indoor environmental conditions. Multiple indoor environmental factors can be improved within the same building. For the estimate of cost savings, we will assume that a 20% to 50% reduction in SBS symptoms is practical in office buildings. The corresponding annual productivity increase is on the order of $10 to $30 billion.

The Cost of Improving Indoor Environments

In two example calculations, Fisk (2000a) compares the cost of increasing ventilation rates and increasing filter system efficiency in a large office building

[32]Most of these studies have taken place in buildings without unusual SBS problems, thus, we assume that the reported changes in symptom prevalences with building factors apply for typical buildings.

[33]Adjusted odds ratios (ORs) for the association of symptom prevalences to individual environmental factors and building characteristics are frequently in the range of 1.2 to 1.6. Assuming a typical symptom prevalence of 20%, these ORs translate to risk ratios of approximately 1.2 to 1.5, suggesting that 20% to 50% reductions in prevalences of individual SBS symptoms or groups of symptoms should be possible through changes in single building or indoor environmental features.

with the productivity gains expected from reductions in health effects. The estimated benefit-to-cost ratio is 14 and 8 for increased ventilation and better filtration, respectively. Similar calculations by Milton (2000) result in a benefit-to-cost ratios of three to six for increased ventilation, neglecting the benefits of reduced health care costs which are about half of the total benefit. For many other measures that should increase productivity, we would expect similarly high benefit-to-cost ratios. For example, preventing or repairing roof leaks should diminish the need for building repairs in addition to reducing allergy and asthma symptoms. Also, some measures, such as excluding indoor tobacco smoking or maintaining pets outdoors of the houses of asthmatics, have negligible financial costs.

Other changes in buildings that have been associated with improved health may have higher costs than increases in ventilation rate, improved filtration, minimizing pollutant sources, and better maintenance. For example, reducing occupant density by a factor of two would increase building construction or lease costs by a factor of two and also considerably increase energy costs per occupant. However, even such changes to buildings may be cost effective in some situations because annual salaries plus benefits are approximately 50 times larger than annualized construction costs or rent (Woods 1989).

Implications for the U.S. Department of Energy

A Scenario for High Performance Buildings

The enormous health cost resulting from our current way of designing, constructing and operating buildings poses a major societal challenge. How can we design and operate buildings that promote health and productivity? How can we improve our homes, workplaces, schools, hospitals and other buildings so they are positive environments for the users? Fanger (2000) has suggested a possible paradigm shift. Over the next two decades, the current goal of providing an adequate indoor environment may be replaced by the goal of providing excellent indoor environments that maximize the health, satisfaction, and performance of building occupants. Factors underlying such a paradigm shift include the increasing affluence of the U.S. population, increased expectations for excellent health, the desire to contain health care costs, and the rapidly increasing evidence that IEQ affects health and productivity. Incorporation of IEQ issues in the green building movement and the increasing use of environmental consultants in new building projects may be the visible start of this paradigm shift. If this shift occurs, there will be significant changes to the designs,

furnishings, operation, and maintenance of buildings with many potential implications for building energy use

Role of the U.S. Department of Energy

A leadership role for the US Department of Energy is to undertake aggressive research and technology transfer programs which: (1) help stimulate the paradigm shift toward excellent indoor environments, thereby improving the health and economic well-being of the US population and the competitiveness of US businesses; and 2) guide the US response so that energy-efficient technologies and practices are used whenever possible to provide excellent IEQ.

Such a role would be consistent with DOE's mission as an agency that seeks to benefit the U.S. public and U.S. businesses, in this case by developing a scientific foundation for improvements in health and productivity. This role would also be fully consistent with DOE's energy-efficiency mission. Many technologies and practices that reduce building energy use can also improve IEQ (IPMVP 1998, Fisk and Rosenfeld 1998, Fisk 2000b); thus, health and productivity gains could become a new stimulus for building energy efficiency. On the other hand, if DOE largely ignores this issue, building designers and operators may choose energy-inefficient methods of improving IEQ since the economic value of productivity gains will often outweigh the energy costs.

This role for DOE is also consistent with DOE's mission and history of advancing science and technology in the buildings' arena. In addition to a long-standing but modest-size program of research on building ventilation, IEQ, and health, DOE and its contractors have unique expertise and research capabilities related to whole-building performance, HVAC, building envelopes, and building control systems as well as established connections to buildings' industries and established programs for promoting improvements to buildings. The DOE expertise in buildings, unmatched by that in any other governmental or non-governmental organization, is essential for this area of research because improvements in IEQ that enhance health depend on changes to the design, operation, use, and maintenance of buildings.

DOE's activities in this field could also be a source of increased prosperity. There is a growing realization that science and technology have been a major source of prosperity in the US. Per unit of investment, a research and technology program explicitly focused on IEQ, health, and productivity should be particularly effective in enhancing prosperity,

Coordination with Other Agencies

An expanded research and technology transfer program in this area by DOE would need to be coordinated with other governmental and private sector programs. In the federal sector, EPA has IEQ programs, with a greater focus on IEQ education and policy than on research, and NIOSH has a modest program, primarily focusing on the relationship of the non-industrial work environment with asthma. Additionally, NIH supports a much larger program of relevant research, primarily basic health research on asthma, allergy, infectious disease (but not the influence of buildings on infectious), and toxic effects of metals and pesticides, typically without a strong contribution from the field of building science. There are minimal overlaps between the programs of different federal agencies. While all these agencies have an important role, their programs on IEQ are modest and focused, and do not obviate the need for the DOE role with a much larger focus on the building science and energy aspects of IEQ and their relationship to health and productivity.

Nature of Knowledge Gaps

A recent review by the US General Accounting Office (GAO 1999) identified the broad categories of IAQ-related knowledge gaps:

1. The identity and sources of pollutants;
2. Mechanisms by which people are exposed to them;
3. The health effects resulting from prolonged and intermittent exposures to low-level concentrations of chemical and biological pollutants as well as complex pollutant mixtures;
4. The most cost-effective strategies for reducing pollutant sources, exposures, and consequent health effects.

The GAO review stresses the importance of multidisciplinary research approaches to this research.

Research and Technology Transfer Needs of Particular Relevance for DOE

Many features of building design, operation, and maintenance affect both occupant health/productivity and building energy consumption. An expanded DOE research and technology transfer program on the interrelationships among buildings, health, productivity, and energy could focus most explicitly on these

building design, operation and maintenance features. In some instances, the health benefits may be adequately documented and DOE-supported work could emphasize technology development and demonstration. In other instances, DOE is already supporting technology development or energy-performance assessment, but additional work is necessary to quantify and demonstrate the health benefits. The subsequent paragraphs describe these more specific research and technology transfer needs. Considerable but not exclusive emphasis has been placed on "win-win" opportunities for research and technology transfer that could improve health and simultaneously save energy.

Building Ventilation

The evidence that increased rates of outside air ventilation generally lead to improvements in perceived air quality, satisfaction with air quality, and health is becoming very persuasive (Seppanen et al. 1999). Consequently, a shift toward higher ventilation rates or more effective methods of controlling pollutant exposures with ventilation seems inevitable. In general, higher ventilation rates will increase building energy use and peak energy demands. [In U.S. residential and service-sector buildings, an estimated 25% of energy use is for ventilation (Orme 1998)]. However, DOE could help to shape the response to the emerging information so that increased energy consumption and peak demands are minimized. In addition, DOE can help to develop and promote use of some HVAC technologies that simultaneously increase ventilation rates (or ventilation efficiencies) and save energy. The following ventilation-related topics should be of particular interest to DOE:

Minimum Ventilation Requirements

Existing data on the relationship of ventilation rates with health outcomes are predominately from studies in moderate to large office buildings located in temperate or cool climates (Seppanen et al. 1999) and most of these studies have employed ventilation rates less than 10 L s-1 per person. There remain very strong needs for studies: of the potential benefits of increasing ventilation rates above 10 L s-1 per person; of ventilation requirements in humid climates; and of ventilation requirements in other types of buildings such as small offices, schools, retail buildings, and dwellings. In addition, since there appears to be no threshold ventilation rate above which health outcomes do not improve (Seppanen et al. 1999), future research needs to quantify the dose-response relationships between ventilation rates and health outcomes so that the

magnitude of health benefits can be weighed against incremental energy and equipment costs.

Better Measurement And Control of Ventilation Rates

In U.S. residences, rates of ventilation depend on the quantity of accidental cracks and holes in building envelopes and ducts, on weather conditions, and on window and exhaust fan use. Even in mechanically-ventilated commercial buildings, HVAC systems very rarely include integral systems for measuring and controlling minimum rates of outside air supply; thus, ventilation rates are poorly controlled. The minimum ventilation rates measured in surveys of such buildings often differ substantially from the minimum ventilation rates specified in the applicable codes (Seppanen et al. 1999, Fisk et al. 1992, Lagus Applied Technologies 1995, Teijonsalo et al. 1996, Turk et al. 1989). While the problems associated with measurement and control of outside air ventilation rates have been recognized for many years, there has been little progress toward overcoming the problems. The large range of ventilation rates among buildings suggests an opportunity to improve health and satisfaction with air quality by increasing ventilation rates in buildings with low ventilation rates and decreasing ventilation rates in buildings with high ventilation rates. Due to the dose-response relationships between ventilation rates and health outcomes (Seppanen et al. 1999), the average level of health symptoms and satisfaction with air quality might be improved without increasing the total ventilation rate of the building stock or increasing the associated energy use. Consequently, research and technology transfer in needed on energy-efficient means of measuring and controlling building ventilation rates.

Heat Recovery from Ventilation Air

Heat recovery systems that transfer heat (and sometimes moisture) between ventilation exhaust airstreams and the incoming outside air can diminish the energy required for ventilation. These systems are used commonly in northern Europe but rarely in the regions of the US with similar climates. Increasing ventilation rates will make heat recovery more cost effective. The technologies required for heat recovery from exhaust ventilation air are already available, but there is a need for demonstrations and guidelines on how and when to properly implement and operate these systems. By quantifying and demonstrating the benefits and costs of increased ventilation with heat recovery DOE can stimulate the market for these strategies.

Displacement Ventilation

A ventilation technology used commonly in Europe, but very rarely in the U.S., is displacement ventilation. This technology supplies air near the floor and produces an upward airflow pattern that is more effective in limiting pollutant exposures than an equivalent amount of well-mixed ventilation. Relative to conventional mixing ventilation, displacement ventilation also removes warm air more effectively. Displacement systems usually supply 100% outside air, increasing ventilation rates relative to conventional systems that supply predominately recirculated air; consequently, heat-recovery systems are often combined with displacement ventilation for energy efficiency. Increased use of displacement ventilation, where appropriate, could reduce health effects and, in some cases, save energy. Research and technology transfer is needed to identify and demonstrate the best opportunities for displacement ventilation.

Task Ventilation

Breathing rates are about 0.1 L s-1 per person, only 1% of the rate of the rate of outside air supply to buildings (Fanger 2000). Task ventilation (sometimes called personal ventilation) systems that supply outside air preferentially to the breathing zone may be able to substantially reduce pollutant exposures and improve health while maintaining or even reducing quantities of outside air. These systems supply air near each occupant's breathing zone. Moderate, 20% to 50%, exposure reductions have been demonstrated for some commercially-available air supply technologies (Faulkner et al. 1993,1998); however, optimization of the ventilation performance of these systems should bring even larger reductions in exposure.

Evaporative Cooling

In some climates, direct or indirect evaporative cooling systems can replace compressor-based cooling. These evaporative systems often supply 100% outside air; consequently, they increase ventilation rates and will reduce indoor concentrations of many indoor-generated pollutants. Energy savings relative to compressor-based cooling can be large (e.g., 50%). Research and technology transfer is needed to develop and optimize systems, quantify and demonstrate IAQ and energy performance gains, and evaluate and address concerns about maintenance and increased indoor humidities.

Moisture and Humidity Problems

Figure 3 illustrates the strong relationship of adverse respiratory and asthma symptoms with moisture problems or the mold contamination commonly associated with moisture problems. Many of these moisture problems are a consequence of water leaks in building envelopes, particularly roofs. Other moisture problems result from condensation of water vapor in walls or from inadequate humidity control by HVAC systems in humid climates. The extent of mold contamination resulting from a moisture problem appears to depend on the selection of building materials. In addition to adversely affecting health, moisture problems degrade the thermal performance of building envelopes, increase energy use, and cause extensive materials damage requiring costly repairs. The prevalence and severity of moisture problems are not fully understood, but a very significant number of buildings are affected. For example, in the U.S. Census data about 15% of houses report water leakage from outdoors (Committee on the Assessment of Asthma and Indoor Air 2000). DOE has a broad range of relevant expertise on building envelope performance (including roofs and foundations), on air and moisture transport through envelopes, and on HVAC performance. Expanded DOE research and technology transfer in this field could help to improve health of the U.S. population, save energy, and prevent costly damage to U.S. buildings.

Higher indoor humidities are associated with increased levels of house dust mites (Chapter 8, Committee on the Assessment of Asthma and Indoor Air 2000). The allergens from dust mites, arguably the most important of allergens for humans, are associated with both the development and exacerbation of asthma (Chapter 5, Committee on the Assessment of Asthma and Indoor Air 2000). Particularly elevated indoor humidities, e.g., above 80% RH, can also facilitate growth of molds indoors; however, the influence of more moderate humidities on indoor mold growth is uncertain (Chapter 8, Committee on the Assessment of Asthma and Indoor Air 2000). Again, there is a link to energy -- maintaining low humidities during air conditioning increases energy use. Many associated research questions remain. The relationships of humidity to dust mite and mold contamination are still inadequately understood. Additionally, research, technology development, and technology transfer efforts are needed to improve humidity control by HVAC systems.

Efficient Air Filtration

Air filtration (or other particle air cleaning systems) show some promise in moderately reducing allergy and asthma symptoms (Chapter 10, Committee on

the Assessment of Asthma and Indoor Air 1999) and portable air cleaners are commonly used by allergic and asthmatic individuals. In addition, more efficient air filtration systems in HVAC systems can dramatically reduce indoor concentrations of fine particles from outdoors (Fisk et al. 2000c). There is persuasive evidence that death rates, hospital admissions, and respiratory symptoms increase with higher outdoor particle concentrations (EPA 1996). Since people are indoors 90% of the time, the exposures to these outdoor particles occur predominately indoors. Consequently, one would expect that the adverse health effects associated with outdoor particles could be substantially reduced through the use of more efficient filtration systems; however, these benefits have not been demonstrated. Once again, there are strong ties with building energy use. A 200 W portable air cleaner, operated continuously, would consume $170 of electricity per year. More efficient filters in HVAC systems also tend to increase fan energy requirements unless the filter is designed for a low airflow resistance. Research is needed to determine when particle air cleaning is (or is not) effective in improving health and to evaluate and demonstrate energy and cost effective efficient methods of particle air cleaning.

Better Indoor Temperature Control

Despite the significant attention placed on thermal comfort by building professionals, dissatisfaction with indoor thermal conditions is the most common source of occupant complaints in office buildings (Federspiel 1998). In a large field study (Schiller et al. 1988), less than 25% of the subjects were moderately satisfied or very satisfied with air temperature. Also, 22% of the measured thermal conditions in the winter, and almost 50% of measured thermal conditions in the summer, were outside of the boundaries of the 1988 version of the ASHRAE thermal comfort zone. Temperatures are also linked to health. In several studies, increased air temperatures are associated with increases in SBS symptoms (Mendell 1993, Mendell et al. 1999) and with reduced satisfaction with indoor air quality (Fang et al. 1998a, 1998b). These findings indicate that greater effort should be placed on HVAC system designs or controls that do a better job than current systems of maintaining thermal conditions within the prescribed comfort zones. Because indoor air temperatures influence occupant health symptoms as well as comfort, the recommended range of indoor temperatures may also need to be reexamined.

HVAC System Maintenance and Operation

Improved maintenance and operation of HVAC systems is another practice with the potential to simultaneously save energy and improve IEQ and health. As discussed above, Sieber et al. (1996) found that large increases in SBS symptom prevalences were associated with evidence of poorer ventilation system maintenance or cleanliness. Many common problems with HVAC system performance (some discussed previously) are reported anecdotally and in published literature. Examples of these problems include: fouling of cooling coils and drain pans by deposited particles and microbial growth; large indoor air temperature oscillations or temperatures maintained outside of the thermal comfort envelope; dirty duct systems; deterioration of HVAC insulation; missing air filters; poor control of indoor-outdoor or inter-room air pressure differences; closed fire dampers; poor air distribution leading to excessive noise, drafts, and thermal comfort problems; insufficient or excessive outside air ventilation; improper damper operation (sometimes the damper linkage is disconnected from the dampers or actuators); fans running backwards, not operating or operating at the wrong times; sensors that are far out of calibration or disconnected; and water leaks. Each of these problems may be due substantially to maintenance and operation problems, although design and construction limitations and errors also play an important role. Research and technology transfer programs are needed to determine the prevalence and underlying causes of these problems and to quantify and demonstrate the energy and IEQ benefits of problem prevention and remediation.

Rethinking HVAC Architectures

Many of the HVAC system problems (mentioned in the previous text) which increase energy use and deteriorate IEQ, have been recognized for many years; however, progress in resolving these problems has been very limited. Improvements to HVAC technologies tend to be incremental and to occur slowly. In parallel with efforts to incrementally-improve existing HVAC architectures, DOE, working in partnership with industry, could rethink HVAC from the ground up with simultaneous goals of improved IEQ, energy efficiency, and maintainability. Innovative HVAC architectures might include many of the following features: outside air supply separated from the system used for thermal conditioning; water used to transport energy around the building (pumping water is more energy- and space-efficient than blowing air through long ducts); individual control of thermal comfort at each workstation; outside air supply near the breathing zone of each workstation with airflow controlled by occupancy sensors; high efficiency particle filters; a modular design with easily

removable and replaceable components so that maintenance occurs in the shop; and advanced sensors and controls. The initial step in this program would be to assemble a highly multidisciplinary panel of experts who will define objectives and work together on innovate HVAC architectures, unfettered by current product designs.

Natural Ventilation

Numerous cross-sectional studies have compared the prevalence of SBS health symptoms experienced in air-conditioned buildings with the prevalence experienced in naturally-ventilated buildings. A large majority of these studies have found that the occupants of the air-conditioned buildings report significantly more symptoms after controlling for other factors (Seppanen and Fisk 2000). The reason for these rather consistent findings is not known. One of the hypothesized explanations is that HVAC systems are sometimes contaminated, for example with microorganisms, deposited particles, and residual oils from the manufacturing process, and become a source of indoor air pollutants. These findings suggest that health symptoms might be reduced through increased use of natural ventilation within commercial buildings located in suitable climates. Naturally-ventilated buildings also tend to use less energy, consequently, simultaneous energy savings and improvements in health may be possible. However, additional research is needed before promoting a shift toward natural ventilation. Within the U.S., there has been only one modest-size study that compared symptom prevalences between naturally-ventilated and air-conditioned buildings (Mendell et al. 1996). Also, until the cause of the increased symptoms in naturally-ventilated buildings is known, it is premature to conclude that symptom prevalences will be lower in new naturally-ventilated buildings.

Indoor Pollutant Source Reduction

The most effective method of controlling the indoor concentrations of many indoor-generated air pollutants is to eliminate or reduce the sources present indoors. Many of these sources depend on the design, furnishing, operation, and maintenance of the building; for example, the selection of building and HVAC materials and office equipment. Building ventilation requirements are diminished when indoor pollutant source strengths are reduced; thus, indoor pollutant source reduction can save energy. Research and technology transfer efforts are needed to identify the sources that do and do-not affect health and to develop and demonstrate methods of eliminating or reducing the important sources.

Conclusions

1. There is relatively strong evidence that characteristics of buildings and indoor environments significantly influence the occurrence of communicable respiratory illness, allergy and asthma symptoms, sick building symptoms, and worker productivity.
2. Theoretical and empirical evidence indicate that existing technologies and procedures can improve indoor environments in a manner that increases health and productivity. Estimates of the potential reductions in adverse health effects are provided in Table 1.
3. Existing data and knowledge allows only crude estimates of the magnitudes of productivity gains that may be obtained by providing better indoor environments in a manner that improves health; however, the projected gains are very large. For the U.S., the estimated potential annual savings plus productivity gains, in 1996 dollars, are approximately $20 billion to $50 billion, with a breakdown as indicated in Table 1.
4. Over the next two decades, the current goal of providing an adequate indoor environment may be replaced by an emphasis on providing excellent indoor environments that maximize the health, satisfaction, and performance of building occupants. Factors underlying such a paradigm shift would include increasing affluence of the U.S. population, increased expectations for excellent health, the desire to contain health care costs, and the rapidly increasing evidence, summarized in this paper, that IEQ affects health and productivity.

Table 1

Estimated Potential Productivity Gains from Improvements in Indoor Environments

Source of Productivity Gain	Potential Annual Health Benefits	Potential U.S. Annual Savings or Productivity Gain (1996 $ billion U.S.)
Reduced respiratory illness	16 to 37 million avoided cases of common cold or influenza	6–14
Reduced allergies and asthma	8% to 25% decrease in symptoms within 53 million allergy sufferers and 16 million asthmatics	1–4
Reduced sick building syndrome symptoms	20% to 50% reduction in SBS health symptoms experienced frequently at work by ~15 million workers	10–30

5. A leadership role for the U.S. Department of Energy is to undertake aggressive research and technology transfer programs which: (1) help stimulate the shift towards excellent indoor environments, thereby improving the health and economic well-being of the US population; and 2) guide the U.S. response so that energy-efficient technologies and practices are used whenever possible to provide excellent IEQ. Research and technology transfer topics that provide opportunities for simultaneous energy savings and improvements in health include the following: building ventilation; evaporative cooling; reducing moisture and humidity problems; efficient air filtration; better indoor temperature control; natural ventilation; HVAC system maintenance and operation; rethinking HVAC architectures; and indoor pollutant source control.

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The Urban Structure and Personal Travel: An Analysis of Portland, or Data and Some National and International Data

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Urban form in the US (and now elsewhere) has tended to be "market driven" with little or no policy input and very little forethought. The advent of new, faster transportation has changed the relative accessibility of vacant land, and both the value to the owner and developers. With improvements in accessibility, more newly developable land becomes available, increasing its value to the owner and decreasing the cost of vacant developable land. Making it more possible to live at lower density at an affordable cost. This has occurred with the advent of commuter rail (in a limited band along the corridors), and to a much larger degree, with the advent of the car, ubiquitous highways, and later, high-speed freeways. Lewis Mumford[2,3] has most aptly and intuitively described this response of urban form to the change in transport supply.

When people in Portland were surveyed on their residential choices, they clearly favored living on acreage in the country, with close access to urban amenities, somewhat paradoxical and not possible for the majority. This is the picture that has been sold to sell suburbia, with the belief that it would be possible with enough freeway construction.

This classic trade-off between travel cost (mostly time) and the price of land (and hence the ability to afford larger pieces of it), paradoxically, is at the root of traffic congestion and an increase in road costs. To get a larger home on a larger lot than would be possible otherwise a people accept more distance between home and work (Edwin Mills[4]). If the full cost were assigned to the new suburban dwellers – both in time, and in the cost of highway construction, a rational economic decision could be made. However estimates of the portion of highways built with

[1]Note that the contents present the views of their authors, not necessarily those of the Department of Energy, RAND, or any other organization with which the authors may be affiliated.

[2]Lewis Mumford (1961), "The City in History," Secker & Warburg.

[3]Lewis Mumford (1964), "The Highway and the City," Secker and Warburg.

[4]Edwin S. Mills (1972), "Studies in the Structure of the Urban Economy," Johns Hopkins Press.

user funds (gas tax and registrations) ranges from 60% to 65%. Given that residents of the inner city and suburbs pay for a large portion of this, the new marginal suburban dweller is initially highly subsidized. This is later rectified as new fringe dwellers continue to arrive at this "cheap" low-density land until the roads are congested and the time costs are no longer attractive. This leads in turn to an outcry against congestion and a plea for further road improvements, restarting the cycle.

As highways congest, there is a perception that there is a cost of congestion – the time lost when traveling in congestion as compared to uncongested travel time. This is indeed the argument made by economists in justifying investment in highways. This presumes that travel needs of each individual are fixed and immutable in terms of frequency and origin-destination patterns. In fact data show that the use of time for travel is fairly constant, and that travelers modify their travel demand (choose different destinations, different times of day, or forgo some travel – sometimes with e-substitution or in-home activities). They also chain activities, rather than leaving home for a single activity, this is more time-efficient.

In Portland, Oregon, there has been a desire to understand the mechanisms leading to travel demand, and the part played by urban design and the configuration of land uses in the urban region. Portland data show that residents in denser, inner-city, mixed use areas consume significantly fewer miles of car travel, substituting slow modes, such as walking, bicycling and transit. Primarily lower-order (slow) streets serve these inner city dwellers. These have some congestion, so that car mobility, expressed as speed, is sharply reduced. Yet the data suggest that these people spend much the same time traveling, and have as many out of home activities as their suburban cousins.

The conclusions that can be drawn from these data lead to a different point of view from those urban planners and traffic engineers who favor building their way out of the problem with more freeways and more mass transit. Their focus is in the reduction of traffic congestion, creating more mobility (speed). The point of view in this presentation is that the real issue is accessibility. In other words, how many activity locations can you get to in a given amount of time? This argument contends that activity opportunities per hour of travel are more important than miles per hour. One could go further, and suggest that the quality of life is improved when the number of activities per hour by different travel modes is improved – accessibility on foot, bike and transit, as well as the car. This becomes important when including those too young to drive (and their harried parents), and those becoming too old to drive (a rapidly growing sector of the population). Two things, the speed of travel *and the density of activity opportunities*

affect activity opportunities per hour. The development of a slightly denser environment, and the change of zoning policies to promote more mixed use (shops, schools, restaurants, close to houses) can reduce car use, and cold starts. This is a shift in focus that saves energy and promotes a healthier environment. The substitution of walking time for riding time is an additional health benefit.

This issue becomes, however, one of policy. In Oregon the policies that affect development decisions are twofold: the desire to minimize the loss of valuable farmland in the Willamette Valley to urban development and the desire to minimize pollution and energy consumption. Given these policies, there has been an attempt to include the effects of urban form (juxtaposition of households and activity locations on a macro scale) and urban design (mix of uses on a micro scale, such as mixed use zoning) in planning for the Portland region. Most of this plan evaluation in Portland is carried out using transportation models developed from a household activity and travel survey carried out in the Portland metropolitan area in 1994 and 1995.

The data from this household activity and travel survey are the source for much of the following discussion.

Measures of Urban Density and Land Use Mix

The study of the interaction of urban form or urban design and transportation demand has a long history. (See Buch[5], Cervero[6], Cambridge Systematics Inc.[7],

[5]M. Buch and M. Hickman (1999), "The Link Between Land Use and Transit: Recent Experience in Dallas," paper presented at the 78th. Annual Meeting, Transportation Research Board, Washington, D.C.

[6]R. Cervero (1991) "Land Use and Travel at Suburban Activity Centers," Transportation Quarterly, Vol. 45, pp. 479–491; R. Cervero (1996) , "Mixed Land-Uses and Commuting: Evidence from the American Housing Survey," Transportation Research A, Vol. 30, pp. 361–377; R. Cervero and R. Gorham (1995), "Commuting in Transit Versus Automobile Neighborhoods," Journal of the American Planning Association, Vol. 61, pp. 210–225; R. Cervero and K. Kockelman (1997), "Travel Demand and the 3Ds: Density, Diversity, and Design," Transportation Research D, Vol. 2, pp. 199–219; R. Cervero and C. Radisch (1996)"Travel Choices in Pedestrian Versus Automobile Oriented Neighborhoods," Transport Policy, Vol. 3, pp. 127–141.

[7]Cambridge Systematics, Inc. (1994), "The Effects of Land Use and Travel Demand Management Strategies on Commuting Behavior," Technology Sharing Program, U.S. Department of Transportation, Washington, D.C., pp. 3-1– 3-25.

Dunphy[8], Ewing[9], Sun[10], Frank[11], Handy[12], Hess[13], Holtzclkaw[14], Kockelman[15], McNally[16] Noland[17], Parsons Brinckerhoff, Quade and Douglas[18], Rutherford[19] and Schimek[20]). The results have been mixed and inconclusive. This may have been due to data limitations, and the use of density measures based on arbitrary polygons, such as census geography (tracts), or a regular grid (cells). These are unrelated to destinations available within walking distance, and have serious boundary effect problems when using disaggregate data. (A traveler may reside inside and near the boundary of a polygon that is of low density, and yet be next to a high density of activity opportunities in the next-door polygon). At least one researcher (Kockelman) has sought to compensate for this by including effects of neighbor polygons (in this case, cells).

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[9]R. Ewing (1995)"Beyond Density, Mode Choice, and Single-Purpose Trips," Transportation Quarterly, Vol. 49, pp. 15–24; R. Ewing , M. DeAnna, and S. Li (1996) "Land Use Impacts on Trip Generation Rates," Transportation Research Record 1518, pp. 1–7. (Data reanalyzed by Fehr & Peers.)

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[11] L.D. Frank and G. Pivo (1994b), Relationships Between Land Use and Travel Behavior in the Puget Sound Region, Washington State Department of Transportation, Seattle, pp. 9–37.

[12]S. Handy, (1993), "Regional Versus Local Accessibility: Implications for Non-Work Travel," Transportation Research Record 1400, pp. 58–66; S. Handy (1996), "Urban Form and Pedestrian Choices: Study of Austin Neighborhoods," Transportation Research Record 1552, pp. 135–144.

[13]P. M. Hess et al. (1999), "Neighborhood Site Design and Pedestrian Travel," paper presented at the Annual Meeting of the Association of Collegiate Schools of Planning, American Planning Association, Chicago.

[14]J. Holtzclaw (1994), Using Residential Patterns and Transit to Decrease Auto Dependence and Costs, Natural Resources Defense Council, San Francisco, pp. 16–23.

[15]K. M. Kockelman (1997), "Travel Behavior as a Function of Accessibility, Land Use Mixing, and Land Use Balance: Evidence from the San Francisco Bay Area," paper presented at the 76~ Annual Meeting, Transportation Research Board, Washington, D.C.

[16]M. G. McNally and A. Kulkarni (1997), "An Assessment of the Land Use-Transportation System and Travel Behavior," paper presented at the 76"~ Annual Meeting, Transportation Research Board, Washington, D.C. (Fehr & Peers conducted expanded analysis of database, 1999)

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Portland Data: A Microanalysis

The Portland data have been organized differently from most of that in the previous research. It uses a continuous measure of density, or mix, that does not utilize polygons. This has been made possible because use has been made of a household activity and travel diary designed for the development of an urban travel model. The data is discrete (disaggregate), with all household and traveler activity locations geocoded to coordinates accurate to within a few feet. The availability of land use data organized within a Geographic Information System (GIS) and available at the parcel level has made the continuous density measures possible. The data comprises all the travel to activities, by all modes, over a two-day period for over 6000 households in the Portland region. The data includes activities that did not include the need to travel.

Density measures were made using the GIS, by capturing the number of jobs, retail jobs, acres of park, number of minor intersections, households, (any objective measure that might be useful) by distance band (1/4 mile, _ mile, _ mile, 1 mile, etc.) from the household, or the activity location. With the assumption that these are distances consistent with a 5-minute walk, 10-minute walk and so on. The hypothesis was that the density a household's travelers are interested in is the density of activity locations (places to do things – work, shop, and play, do business and so on). The availability of other households is of relatively minor importance. Other studies have posited that housing density is important, while it is true that sometimes housing density is correlated with the availability of other activity density (a surrogate), it often is not, in truth this is a highly variable circumstance – so leads to inconclusive conclusions.

Some Density Measures in the Portland Study

For the purposes of this presentation, the strongest variables in the Portland study that show distinct land-use effects emerging from the development of travel models have been summarized and put into a descriptive form. The travel models used multivariate and multinomial regressions, both linear and non-linear, but primarily of the logit (logistic regression) form.

For the purposes of developing descriptive tables and graphs, all of the measures have been assigned to each of the surveyed households. They have then been grouped in 10 quantiles (deciles) for each measure, so that means for each decile can be computed and shown. To give some sense of real values, the range of values for the measure for each decile are also shown here. *The deciles are always*

numbered 1 through 10, 1 is the least "urban" (ex-urban), 10 is the most "urban", usually in the inner Westside, the inner Eastside and surrounding the downtown.

Mix. "Mix" is a number used to define the balance and intensity of jobs and households. This is the product of households and workers within a _ mile radius of the point of interest, divided by the sum of households and workers in the _ mile radius. The households are normalized to employment by multiplying the household in _ mile by the ratio of regional employment to regional households. Where $HH_{1/2m\_N} = HH_{1/2m}*(EMP_{Reg.}/HH_{Reg.})$. (Subscript Reg. is total

Table 1

Mix Decile Rangels

Deciles	*Range*	
Mix	Lower	Upper
1	0	0
2	0	2
3	2	18
4	18	41
5	41	71
6	71	109
7	109	161
8	162	245
9	245	426
10	426	2335

regional, HH=households, EMP = employment, subscript N denotes normalized, subscript 1/2m denotes _ mile radius)

$$MIX= (HH_{1/2m\_N} * EMP_{1/2m}) / (HH_{1/2m\_N} + EMP_{1/2m})$$

Workers—1 mile. Another measure is the total number of workers within 1 mile of the household, or activity location. The range in Portland ran from 0 to 116,000.

Retail—1 mile. A similar measure is the number of retail workers within 1 mile of the household or activity location. This measure is very useful, as retail density also serves, to some extent as a surrogate for other services, and turns out to be the most important measure of the degree of urbanization in our models.

A mile represents about 20 minutes walking.

Local Intersections—Miles. Yet another measure is the number of local intersections within _ mi. radius. This is a surrogate for continuity of the walking environment. For a future or policy analysis it could be replaced with the number

of path intersections/local intersections in a design that has few local streets with but an overlay of pedestrian paths. The range in Portland is from 1 to 310 local intersections in a _ mile, with the top 3 deciles (most urban) ranging from 160 to 310.

Urban Index. An urban design index chosen for this paper (Urban Index) is a combination index using the number of retail jobs within a mile of the household combined with the number of local street intersections within a _ mile. These were the strongest urban design variables in multivariate regression analyses.

Table 2

Deciles Retail Jobs 1 mi

Deciles Retail 1 mi.	Range Lower	Upper
1	0	7
2	8	70
3	70	206
4	207	382
5	382	597
6	598	889
7	890	1317
8	1319	1933
9	1941	3395
10	3434	12759

Table 3

Deciles Urban Index—Combination

Deciles	Range LocInt_1/2 Mi		Range Retail_1 Mi	
Urb_Index	Lower	Upper	Lower	Upper
1	1	104	0	188
2	6	217	0	4974
3	61	217	8	6433
4	87	159	70	1316
5	87	229	71	4256
6	105	297	207	5671
7	120	288	384	5449
8	132	309	621	10576
9	146	300	892	12522
10	175	288	1950	12759

Note that here, the combined ranges for the values are shown. Thus decile 10 has more than 175 local intersections within _ mile and more than 1950 retail jobs within 1 mile.

Travel Characteristics Associated with Urban Design/Density

Traditionally, predictive models developed in US practice have their roots in the 1960s and were primarily designed to predict auto travel demand on an uncongested network of streets. As such, surveys did not collect information on "slow modes" – walk and bicycle, or on short trips of less than _ mile. For most

models it was assumed that car ownership was exogenous, or at most related to the variables of household size and income alone. It was also assumed that the quantity of travel to activities was related to car ownership, and household size. These models were developed primarily to guide highway investment. They were later slightly modified to predict transit ridership more completely. Transit ridership models were primarily driven by transit service characteristic (compared to the car for the same journey), and car ownership (assumed exogenous, or at best income driven).

As a part of building predictive models for the Portland Metro area, it was noticed, many years ago, that the traditional predictors of travel quantity used in US practice were not accurate when tested on sub-sets of the households that had significantly different urban characteristics from the mean. It was also noticed that the transit service available to the household, measured as jobs accessible by transit in 30 minutes, the pedestrian environment, measured as retail jobs accessible by walking in 20 minutes and the continuity of the street network, measured as local intersection density, indeed have an effect on cars owned.

The following sections will give an example of an effective car ownership model, estimated using logit regression; a descriptive display of differences within different urban environments; and a series of descriptive displays for other travel metrics. Models for all of these elements will not be shown, as they are complex and interactive.

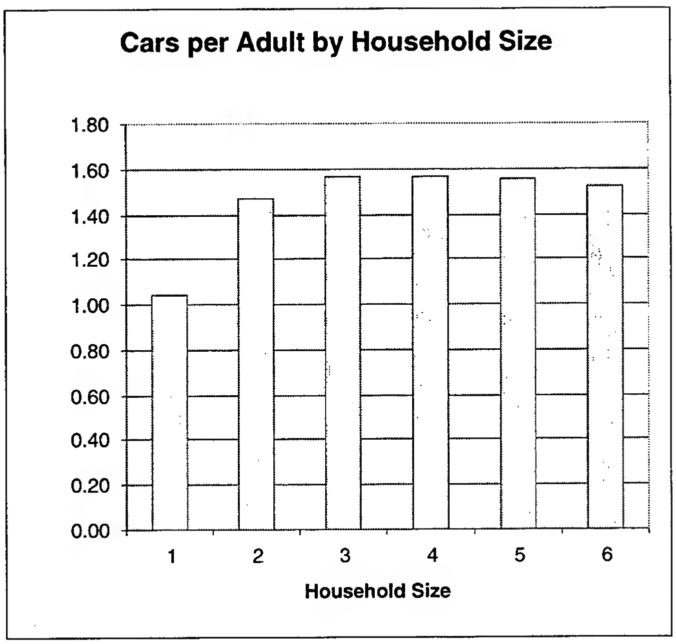
Car Ownership

Car ownership has been traditionally regarded as dependent on household size and income. The Portland data show that theses are certainly variables of interest, however, these days, when there are more cars than drivers, it is of interest to look at cars per adult (here 18+), per household.

Table 4

Cars per Adult by HH Size

HHsize	Mean	Std. Dev.	Freq.
1	1.04	0.65	1851
2	1.47	0.79	2797
3	1.56	0.84	1119
4	1.57	0.87	948
5	1.56	0.86	347
6	1.53	0.90	154
Total	1.39	0.81	7216

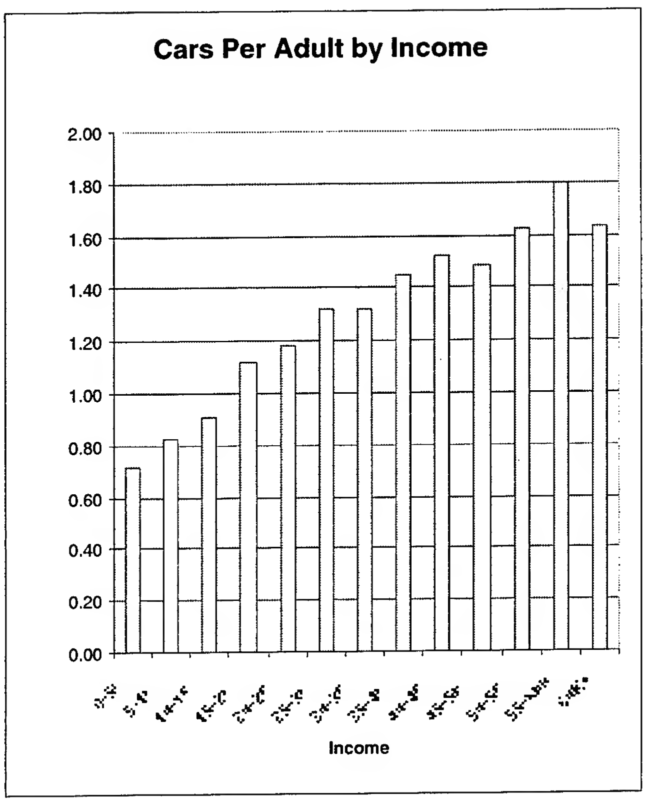


We can also look at cars by income group for the whole region.

Table 5

Cars Per Adult by Income

Income	Mean	Std. Dev.	Freq.
0-5K	0.71	0.63	52
5-10K	0.83	0.78	200
10-15K	0.91	0.75	337
15-20K	1.12	0.71	396
20-25K	1.18	0.73	457
25-30K	1.32	0.64	482
30-35K	1.33	0.69	571
35-40K	1.45	0.88	496
40-45K	1.52	0.79	542
45-50K	1.49	0.71	366
50-55K	1.63	0.82	457
55-60K	1.80	1.07	160
60K+	1.63	0.82	1247
Total	1.39	0.81	5763



We can now move on to look at the car ownership by MIX and Urban Index.

Table 6

Cars Per Adult by MIX Variable

Deciles MIX	Mean	Std. Dev.	Freq.
1	1.66	0.96	1055
2	1.56	0.78	156
3	1.52	0.81	728
4	1.53	0.80	733
5	1.43	0.78	709
6	1.37	0.71	691
7	1.31	0.71	679
8	1.28	0.72	690
9	1.17	0.68	698
10	0.98	0.72	731
Total	1.38	0.80	6870

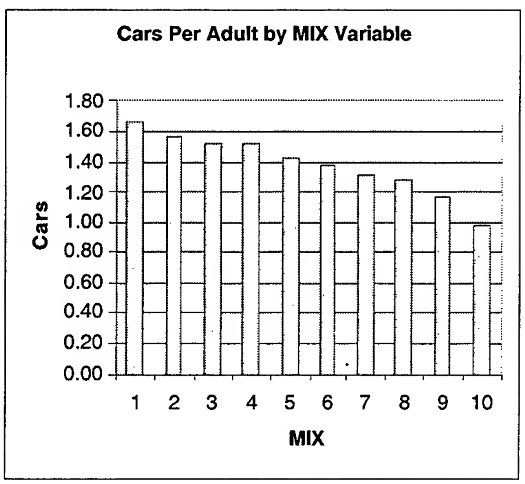
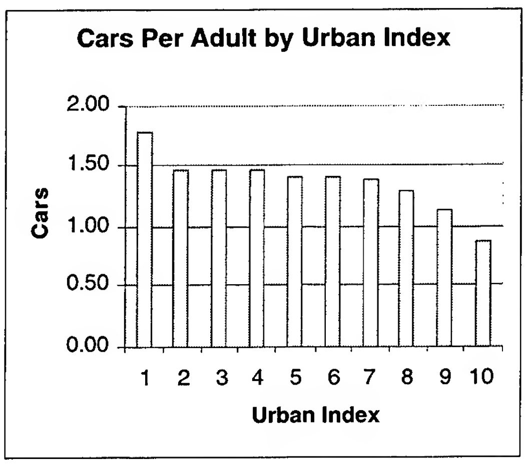


Table 7

Cars per Adult by HH Size

Deciles Urban Index	Mean	Std. Dev.	Freq.
1	1.78	0.92	727
2	1.45	0.74	833
3	1.47	0.85	705
4	1.47	0.76	638
5	1.40	0.79	595
6	1.39	0.77	683
7	1.37	0.73	768
8	1.28	0.71	605
9	1.13	0.71	707
10	0.85	0.65	516
Total	1.38	0.80	6777



Car Ownership Model—An Example

This car ownership model is intended as an example to give the reader some sense of the variables of importance and also to show the statistical fit. The rest of the metrics will be shown descriptively only. Although the models used in Portland account for all of the described effects, they do so in more complex interactive ways, too complex for a paper of this scope.

Table 8

Variables and Coefficients- Car Ownership Model

Cars in HH	Coef.	Std. Err.	z	P>|z|	[95% Conf. Interval]	
1-Car						
ln HH Income	0.9843373	0.1006453	9.78	0	0.7870762	1.181598
Persons in HH	0.2736137	0.1223973	2.235	0.025	0.0337195	0.513508
Workers in HH	0.3385346	0.1287423	2.63	0.009	0.0862044	0.5908648
Adults in HH	0.484109	0.2616866	1.85	0.064	-0.0287874	0.9970053
Retail jobs in 1mi	-0.0001325	0.0000311	-4.264	0	-0.0001934	-0.0000716
Local Int. in 1/2 mi	-0.0020657	0.0019545	-1.057	0.291	-0.0058965	0.0017651
Jobs by Transit 30min	-4.04E-06	1.32E-06	-3.06	0.002	-6.62E-06	-1.45E-06
Constant 1	-8.068329	1.040728	-7.753	0	-10.10812	-6.02854
2-Cars						
ln HH Income	2.115116	0.1191553	17.751	0	1.881576	2.348656
Persons in HH	0.8497877	0.1249471	6.801	0	0.6048959	1.09468
Workers in HH	0.6987862	0.1354029	5.161	0	0.4334013	0.964171
Adults in HH	1.1623	0.265057	4.385	0	0.6427981	1.681802
Retail jobs in 1mi	-0.0002374	0.0000397	-5.976	0	-0.0003153	-0.0001596
Local Int. in 1/2 mi	-0.0031639	0.0020735	-1.526	0.127	-0.0072279	0.0009001
Jobs by Transit 30min	-7.89E-06	1.47E-06	-5.369	0	-0.0000108	-5.01E-06
Constant 2	-21.66061	1.240426	-17.462	0	-24.0918	-19.22942
3-Cars						
ln HH Income	2.252273	0.1408918	15.986	0	1.97613	2.528415
Persons in HH	0.9113492	0.129191	7.054	0	0.6581394	1.164559
Workers in HH	1.160385	0.1471366	7.886	0	0.872003	1.448768
Adults in HH	1.247499	0.2723545	4.58	0	0.7136936	1.781304
Retail jobs in 1mi	-0.0004069	0.0000668	-6.09	0	-0.0005379	-0.000276
Local Int. in 1/2 mi	-0.0052738	0.0022611	-2.332	0.02	-0.0097055	-0.0008422
Jobs by Transit 30min	-8.68E-06	1.79E-06	-4.859	0	-0.0000122	-5.18E-06
Constant 3	-25.01953	1.483462	-16.866	0	-27.92707	-22.112
4+Cars						
ln HH Income	2.222513	0.1840548	12.075	0	1.861772	2.583253
Persons in HH	1.000593	0.1385841	7.22	0	0.728973	1.272212
Workers in HH	1.613175	0.1707538	9.447	0	1.278504	1.947846
Adults in HH	1.516216	0.2836213	5.346	0	0.9603284	2.072104
Retail jobs in 1mi	-0.0002596	0.0000895	-2.9	0.004	-0.0004351	-0.0000842
Local Int. in 1/2 mi	-0.0073351	0.0026612	-2.756	0.006	-0.0125509	-0.0021193
Jobs by Transit 30min	-0.0000104	2.40E-06	-4.349	0	-0.0000151	-5.74E-06
Constant 4	-27.23391	1.976477	-13.779	0	-31.10774	-23.36009

Cars=0 is the comparison choice.

The following logit regression explicitly estimates the probability of owning an discrete number of vehicles:

Multinomial regression	Number of obs = 4953
	chi2(28) =2980.88
	Prob > chi2 = 0.0000
Log Likelihood = -4896.6853	Pseudo R2 = 0.2334

Below is shown the result of model application to disparate urban environments.

Table 9

Region-Wide Application

Cars in HH	Survey%	Model %
0-Cars	4.94	5.79
1-Car	31.15	32.59
2-Cars	44.53	44.54
3-Cars	14.25	12.72
4+Cars	5.12	4.36
Total	100	100

Table 10

Most Urban (Decile 10)

HH-Cars	Survey%	Model%
0-Cars	24.13	25.41
1-Car	51.16	49.37
2-Cars	20.27	21.54
3-Cars	3.86	2.68
4+Cars	0.58	1
Total	100	100

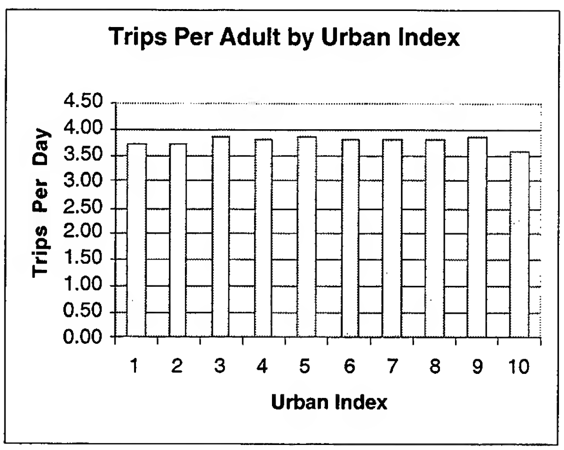
Trips to Activities

In considering the travel behavior exhibited by individual adults, the Portland study indicates that in areas with a high urban index there is a lower car ownership. It therefore might be expected might expected that out of home activities and hence trip-making might be lower. But this is not the case as we can see below. The trip rates are almost constant. A look at trips made to activities reveals little variation across differences in the urban environment.

Table 11

DailyTrips Per Adult by Urban Index

Urban Index	Mean	Std. Dev.	Freq.
1	3.74	2.09	1731
2	3.74	2.06	1865
3	3.88	2.19	1569
4	3.84	2.14	1432
5	3.89	2.23	1255
6	3.81	2.09	1462
7	3.81	2.08	1651
8	3.83	2.18	1202
9	3.89	2.28	1257
10	3.55	2.11	763
Total	3.80	2.14	14187



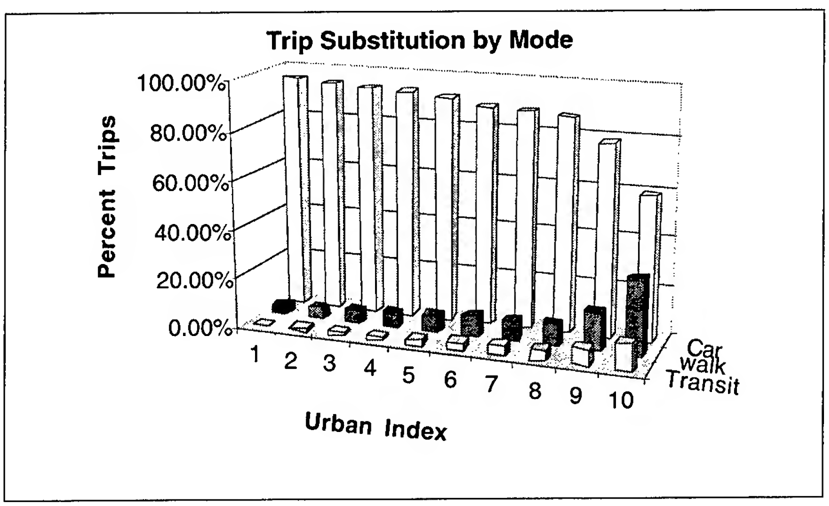
Mode of Travel to Activities—Substitution

Of much more interest is the substitution of modes of travel used, with increasing use of slower modes of walking and transit in the denser parts of the region. Similar behaviors are demonstrated for MIX and various other density variables.

Table 12

Mode Substitution by Urban Index

Urban Index	By Car	Transit	Walk	Total	% Car	% Transit	% Walk
1	3.58	0.02	0.14	3.74	95.68%	0.53%	3.79%
2	3.54	0.04	0.16	3.74	94.51%	1.15%	4.34%
3	3.62	0.05	0.20	3.88	93.33%	1.40%	5.27%
4	3.57	0.06	0.21	3.84	92.99%	1.56%	5.45%
5	3.55	0.08	0.26	3.89	91.25%	2.09%	6.65%
6	3.38	0.11	0.32	3.81	88.66%	3.00%	8.34%
7	3.35	0.15	0.31	3.81	87.89%	3.97%	8.14%
8	3.33	0.16	0.34	3.83	86.90%	4.22%	8.88%
9	3.03	0.26	0.60	3.89	77.85%	6.73%	15.42%
10	2.08	0.39	1.09	3.55	58.53%	10.87%	30.60%
Total	3.36	0.12	0.33	3.80	88.28%	3.14%	8.58%



Vehicle Miles of Travel per Person per Day

Of most interest for the purpose of gauging energy consumption is vehicle miles of travel. This, along with trips (cold starts for cars), is of importance in vehicular emissions, which affect air quality. The Portland study clearly reveals that the areas with the best density of activity opportunities, and the most continuous street network, have significantly lower vehicle miles of travel per person, compared with lower density locations.

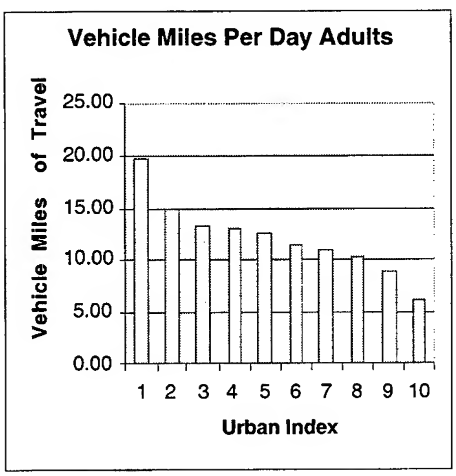
Note that there is a danger of reading too much into the graphic. The areas of high urban index are mainly within the central city. A variable that is not

Table 13

Vehicle Miles Per Adult by Urban Index

Urban Index	Mean	Std. Dev.	Freq.
1	19.82	22.47	1725
2	14.82	17.43	1860
3	13.22	15.69	1565
4	13.11	15.48	1432
5	12.59	15.04	1254
6	11.40	13.75	1457
7	10.80	13.43	1651
8	10.19	13.09	1200
9	9.00	12.51	1253
10	6.28	10.16	763
Total	12.69	16.08	14160

NOTE: Portland data.



discussed in this paper is that of accessibility by car. This could be simply expressed as the number of activity locations accessible by car within 10, 20 or 30 minutes. Put simply, household locations with a high Urban Index in these data are, by nature of their location, also going to have a high value of accessibility by car, even though they are located in areas with very slow car travel. This means that they have many nearby choices by car, which contributes to a reduction in the vehicle miles of travel.[21]

Notional Data—a Macroanalysis

In a more general sense the gross densities and road supply for regions can be looked at to get some sense of the implied relationships between density, road supply and daily vehicle miles of travel per person. The following data were culled from Highway Statistics 1998, Office of Highway Policy Information, Federal Highway Administration.

These data are developed from FHWA's Highway Performance Measurement system (HPMS). The States collect these data individually, with some differences in quality, in other words, some measurement error. These data are developed from traffic counts, which cannot discern the difference between personal travel, commercial and truck travel and travel by non-residents of the region. As such these will show higher values of daily vehicle miles of travel (DVMT) per person than will data from household surveys. Cities are highly idiosyncratic, with various amounts of unbuildable area (bodies of water etc.). Even so the data suggests some relationships on a gross scale. The clear standout is New York, the biggest and also the least homogeneous in structure and density. It has areas of extremely high and extremely low density, with enough high density and mixed use to see significant pedestrian and transit travel, hence the very low DVMT. It is always a surprise to see Los Angeles as the densest urban area in the US, however it is fairly homogeneous, and was developed (as was Portland) in the streetcar era, and so has large areas of regular street pattern, and small single family lots, mixed with multifamily. New York and Boston were shaped in the railroad and streetcar era. The three highest auto-use cities are also the ones that have seen most of their development during the auto-dominant era (Houston,

[21] This raises the issue of macro, rather than micro effects. This has to do with another issue in urban planning, the relative location of households and jobs. Urban transport models are ideally suited to measure response to alternative land-use scenarios that use different ways of locating major employment areas relative to new housing. This exercise is not often undertaken, but can be very useful in determining a policy direction for preferred land-use arrangements. Work done in Portland, in particular the 1000 Friends of Oregon Land Use, Transportation and Air Quality study (LUTRAQ) and the development of Metro's 2040 plan has demonstrated that the combination of micro and macro design policies can reduce car-based travel demand.

Atlanta and Dallas-Ft. Worth.) these are also cities that have been the most aggressive in attempting to serve the demand for auto travel, building freeways in an attempt to avoid congested conditions. They have the lowest density, the largest amount of road space per capita and the highest DVMT per capita. Phoenix is unusual in that initial development followed a no-freeway policy, with a very extensive high-level regular arterial street system, slower than freeways, but with large capacity. The no-freeway policy has been dropped with significant recent freeway building.

All of these cities were chosen for this display because they are freestanding cities with little interaction with others. The data are shown in the following tables (Tables 14 & 15).

The relationships shown by the Portland data are, in a general sense borne out by the national data. However, the national data also suggest that an increased road supply is strongly related to lower overall density and increased vehicle miles of travel. This is probably a circular relationship – initial traffic demand increase (from car availability) leads to more and faster roads, in turn making more lower cost rural land accessible, in turn leading to more fringe development at a lower density, in turn generating more traffic demand, in turn leading to more road construction, and so on.

Acronyms in the tables are DVMT—Daily Vehicle Miles of Travel, ADT—Average Daily Traffic, mi.—miles, Fwy – freeway.

Table 14

DVMT per Capita by Density—US 1998

City/Region (Urbanized Area)	Persons/ Sq. mi.	DVMT/ Cap
Los Angeles	5650	21.7
New York	4140	15.7
San Diego	3660	21.5
Sacramento	3530	20.5
San-Fran-Oak.	3340	21.2
Portland-Vancouver	3140	21.1
Boston	2550	20.5
Denver	2540	22.5
Phoenix	2360	21.5
Seattle	2350	25.5
Dallas-Ft. Worth	2170	29.2
Minneapolis-St Paul	1950	24.2
Atlanta	1600	35.8
Houston	1560	38.4

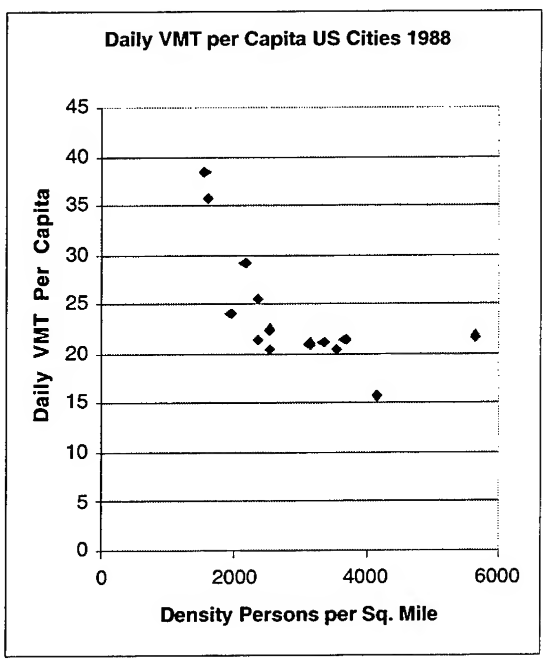
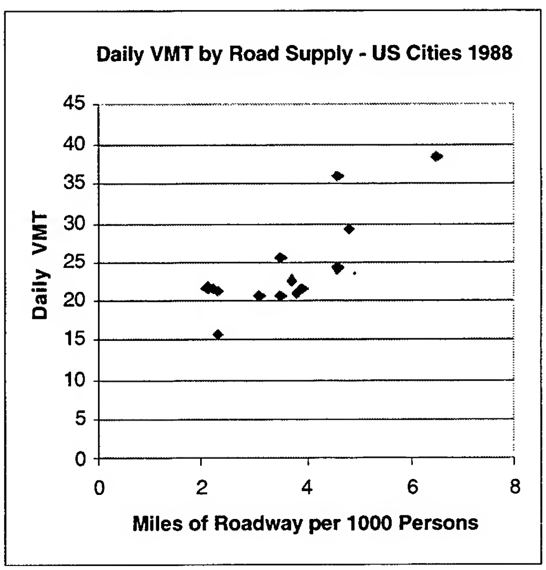


Table 15

DVMT per Capita by Mi. Road/1000 persons US 1998

City/Region	Mi. Rd/ 1000	DVMT/ Cap
Los Angeles	2.1	21.7
San Diego	2.2	21.5
New York	2.3	15.7
San-Fran-Oak.	2.3	21.2
Sacramento	3.1	20.5
Boston	3.5	20.5
Seattle	3.5	25.5
Denver	3.7	22.5
Portland-Vancouver	3.8	21.1
Phoenix	3.9	21.5
Atlanta	4.6	35.8
Minneapolis-St Paul	4.6	24.2
Dallas-Ft. Worth	4.8	29.2
Houston	6.5	38.4



The Use of Time for Travel

Wherever they live and however they travel, people spend about the same amount of time traveling. This was the result of research in the late 1970s and 1980 by Yacov Zahavi, and others[22] into time used in travel as reported in several transportation studies of vastly disparate cities.

Looking at Table 16, it can be seen that whether a person lives in Bogotá, Columbia, Washington DC, Calgary, Santiago, Chile, or Portland, OR, the mean number of minutes spent traveling is similar. What differs is the use of modes of travel and travel system speed. This is not to say that everyone travels for this time, there is a distribution of time in each city, but the means are similar. The same is true for different parts of Portland and for different income groups.

As has been seen, there is significant substitution of slow modes for fast in areas of Portland that have more density and mixed land use. The assumption was that people would go to fewer activities or spend more time traveling. As it happens, they did neither.

Table 16

Daily Mean Time of Travel per Traveler. Hours

REGION	Year	Class 1	Class 2	Total
By Income		**Hi Inc.**	**Lo Inc.**	
Bogotá, Columbia	N/A	1.05	1.78	
Santiago, Chile	N/A	1.09	1.52	
Singapore	N/A	1.14	1.36	
By Mode Used		**Car**	**Transit**	
Washington, DC	1955	1.09	1.27	
	1968	1.11	1.42	
Minneapolis-St. Paul	1958	1.14	1.05	
	1970	1.13	1.15	
All USA	1970	1.06	0.99	
By Car Availability		**0- Cars**	**1+ Cars**	
St. Louis	1976	1.06	1.04	1.04
Nuremberg	1975	1.40	1.26	
Total – No Classification				
Toronto	1964			1.09
Calgary	1971			1.11
Montreal	1971			1.18
Portland, OR*	1994			1.09

Source: Zahavi et al, and Metro

*Portland travel includes pedestrian and bicycle travel – the others only motorized modes.

[22] Y. Zahavi, M. J. Beckman, and Thomas F. Golob, (1981), The 'UMOT'/Urban Interactions. Prepared for the U.S. Department of Transportation, Report No. DOT/RSPA/DPB-10/7.

The following work focuses on the use of time as a way to raise the issue of what are rational and reasonable measures of performance for the evaluation of the transportation system.

Table 17

Time Spent Traveling—Adults by Urban Index

Urban Index	Mean	Std. Dev.	Freq.
1	77.53	69.36	1725
2	60.66	46.38	1860
3	60.19	47.11	1565
4	58.80	41.70	1432
5	59.31	44.41	1254
6	60.93	44.84	1457
7	60.78	46.78	1651
8	61.05	46.41	1200
9	62.81	48.16	1253
10	65.85	50.23	763
Total	62.90	49.81	14160

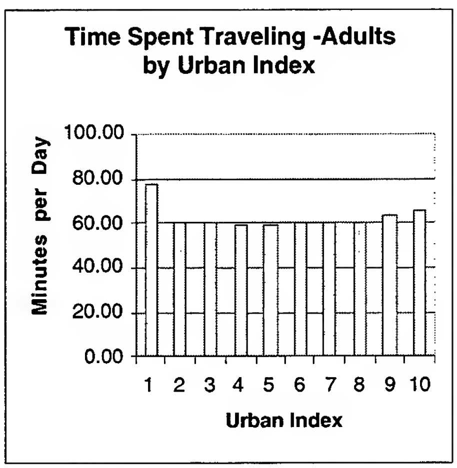
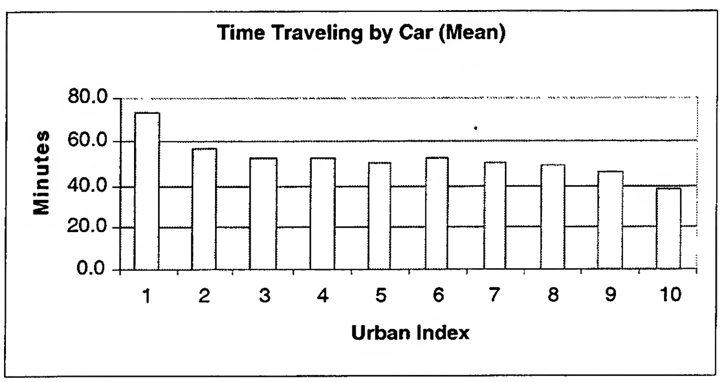


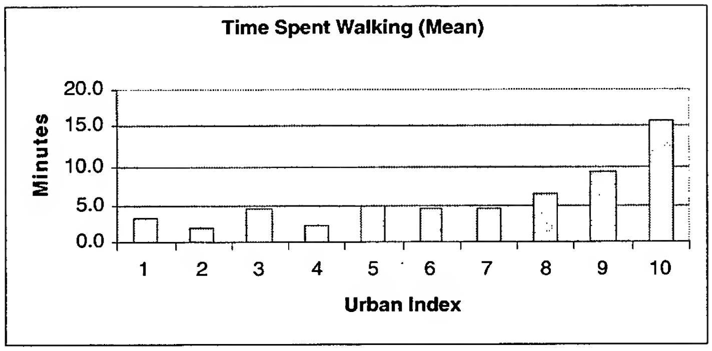
Table 18 and the following graphs show that there is substitution in the use of time among modes, but the total time in travel is similar. It is interesting to note that the third highest urban index shows time spent walking at twice, that of the second highest at three times and the highest at five times that of the suburbs. Remembering that the number of out of home activities did not change among these groups, it is clear that those in the denser areas can accomplish their activity needs, and do so in a healthier way, with no extra use of time.

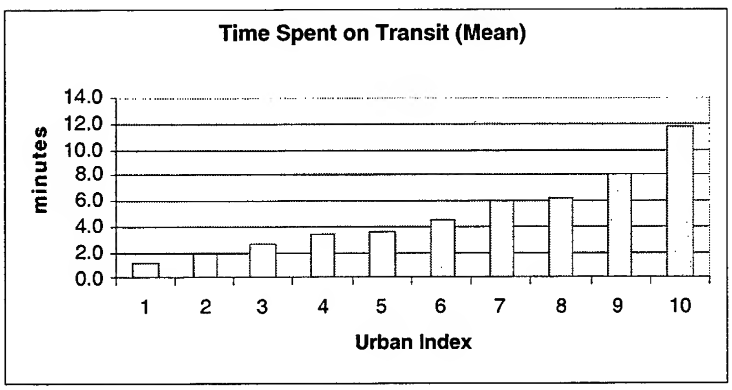
Table 18

Mean Time of Travel by Mode by Urban Index (Minutes)

Urban Index	Time Car	Time Walk	Time Transit	Total	Freq.
1	73.2	3.3	1.1	77.5	1725
2	56.7	2.0	2.0	60.7	1860
3	52.9	4.5	2.8	60.2	1565
4	52.9	2.4	3.5	58.8	1432
5	50.7	5.0	3.6	59.3	1254
6	51.9	4.4	4.6	60.9	1457
7	50.2	4.6	6.0	60.8	1651
8	48.4	6.4	6.3	61.0	1200
9	45.6	9.1	8.1	62.8	1253
10	38.3	15.7	11.8	65.9	763




Time Spent Walking (Mean)
Minutes
20.0
15.0
10.0
5.0
0.0
1
2
3
4
5
6
7
8
9
10
Urban Index

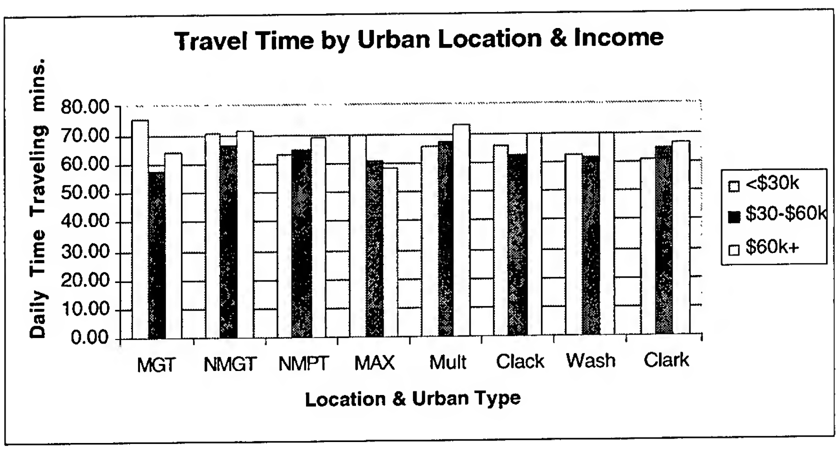

Time Spent on Transit (Mean)
minutes
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1
2
3
4
5
6
7
8
9
10
Urban Index

Moving away from the analysis by Urban Index, to an analysis by the household initial survey strata, within which random samples were taken. The first four are in the City of Portland, going from good transit and mixed land-use to no mix and an average level of transit service, with MAX being households within the light rail corridor. The last four are suburban in nature, with Clark County, Washington having some urban mix. Table 19 shows that there is little difference in time used by both urban structure and income.

Table 19

Daily Travel Time by Urban Location & Income

Survey Strata	Label	<$30k	$30-$60k	$60k+	Total
Mixed+GoodTransit	MGT	75.13	57.78	64.35	66.47
NoMix+GoodTransit	NMGT	70.57	66.52	71.87	69.58
NoMixPoorTransit	NMPT	63.36	65.12	68.69	65.36
MAXCorridor	MAX	69.85	60.94	58.13	62.87
SuburbanMultnomah	Mult	66.14	66.88	73.08	67.92
SuburbanClackamas	Clack	66.10	62.46	69.57	65.74
SuburbanWashington	Wash	62.08	61.77	69.51	64.35
Clark County, WA	Clark	60.39	65.35	66.42	64.51
Total		64.70	64.49	68.45	65.60

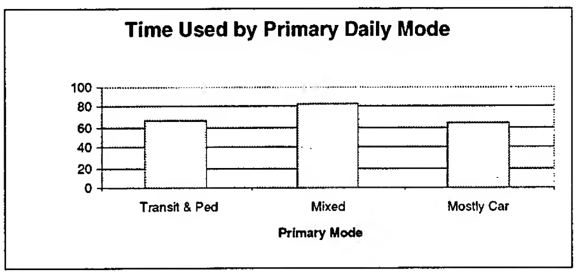


Finally we can look at travel time segmented by travelers that use different modes (Table 20). When we look at all-day travel, very few travelers use only one mode. So the following table is set into three groups – those that do not use a car ("Transit and Pedestrian"), those that mix their modes (more than 25%of their time on walk or transit and less than 75% of their time in a car), and those that are primarily car travelers (more than 75% of their travel time by car).

Table 20

Travel Time by Mode Most Used

Primary Mode	Mean	Std. Dev.	Freq.	Modes
Transit & Ped	64.63401	45.20859	347	All Slow
Mixed	82.14394	43.66445	396	>25% slow
Mostly Car	63.58168	37.80112	3722	>75% car
Total	65.30974	39.31762	4465	



Measures of Performance for Transportation

This section addresses the traditional measures of performance of the transport system (congestion, mobility and time lost to congestion), and suggests other measures that might be more appropriate. The traditional measures always lead to warrants for new road building, leading to higher speeds, leading to more low density suburban development, leading to more congestion and lower speeds, leading to more new roads ----and so on.

Percent Congested

Here congestion is measured as defined in the Highway Capacity Manual, by levels of service A through E, with failure at level "F" (below E). This measure is a one hour peak measure (am or pm), although many cities now recognize that they may have to accept more than one hour congested. This measure is an arbitrary, ad-hoc definition developed by traffic engineers around 1960, during the heyday of highway construction.

These levels of congestion are linked to hourly traffic flows, and can thus be defined from traffic counts (present day) and model forecasts (future). Usually expressed as the percent of roads congested for 1 hour, two hours and so on.

Mobility and Value of Time Lost to Congestion

The next concept is that of mobility, defined as the average speed of the network, or types of highway, often linked to congestion by calculating the free (uncongested) speed and the congested speed and using the ratio as a measure of mobility. This is usually expressed as travel time at free speed over travel time under congestion. The next step is to sum all the excess time for all travelers, calculated by this method, assign a value of time (usually $10 to $20 per hour, or 16 to 32 cents per minute, and calculate the cost of congestion by multiplying the excess time by the value of time.

This approach assumes that the demand for travel is fixed spatially, and not by time. In reality travelers take actions to conserve time – change destination, travel at a different time, chain activities into a single trip, and in the longer time frame, land develops differently, with more density of both housing and activity locations.

Activities Accessible by Time Increment

This is, perhaps the most tempting. It is simply a measure of activity locations accessible within 10, 20, 30, 40 minutes etc. These could be jobs accessible, retail establishments accessible, retail jobs accessible and so on. This could be by fastest mode, or by each mode separately.

As an example, in a system of a given size in terms of people and jobs, a system with _ the speed and twice the density of another system would have exactly the same accessibility measure in terms of activities reachable in a fixed time. If average time used remained constant and the same modes were used, the vehicle miles traveled would be halved. The increased densities, however, also make transit more efficient and usable, and increase the probability of walking.

Energy Use per Capita? Per activity Visited?

These are other ways of thinking, we could look at different land use arrangements, with different transport investments, and calculate energy demand from the system, relatively easy to do with current travel demand models, and very easy to do accurately with Los Alamos' new transport model – Transims.

Conclusions & Recommendations

It has been demonstrated that density, mix and urban design all have an effect on travel demand. It is also strongly suggested that mean travel time consumed by travelers per day is relatively constant, suggesting that the amount of travel (miles) is affected by the travel speed in the network. There is a need to consider changes to both single-use land use zoning and the layout of urban and suburban streets. Different future designs can give different travel, car use can be reduced, and walking and transit use increased – leading to less energy consumed, cleaner air, more exercise in traveling and better health. These elements are already a part of urban planning in Portland. While the private market carries out land development, government can take actions to steer or guide development towards a preferred policy land-use scenario.

When looking at the amount of travel in US cities, it is clear that those cities with lower densities, and a larger road supply consume significantly more vehicle miles of travel.

The three cities that have been mainly formed in the last 50 years, under a policy of plentiful supply of roads and freeways, Houston, Atlanta and Dallas-Ft. Worth

clearly have the best road supply, the lowest densities ***and the most vehicle use*** – Houston and Atlanta in the order of 50% more vehicle miles of travel per capita than comparable sized cities. It is of note that Houston and Atlanta are two of the cities in the US with the most air pollution (along with Los Angeles – a very large city). Urban economic theory and urban land-use forecasting models both suggest that developing land use is strongly affected by the speed of the network. The faster the travel speeds and the more ubiquitous the network, the lower the density developed under free market conditions.

While it is very difficult, politically, to introduce the concept of land use design and control as a part of the solution, and highway over-development as part of the problem, it is a dialog that needs engaging.

There is the need to go much further in developing forecasts that consider the interaction of land-use and transport investment. Currently land-use forecasts are made administratively, or with very little transport supply input, and then are considered fixed while transport solutions are sought. The truth is that different transport investments create different land use futures. There is a real need to carry out forecasts with integrated transport and land-use models. This is a discipline that is very under-developed and in much need of more research.

Enhancing Productivity While Reducing Energy Use in Buildings

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Indoor air quality (IAQ) and air temperature (T) have powerful effects on the efficiency with which work can be performed in schools and offices. Huge amounts of energy are used to keep these parameters constant at levels which represent a compromise between group average requirements for subjective comfort and energy conservation. Human requirements change with task requirements and from hour to hour, so the levels at which T & IAQ are maintained are at best a crude approximation to what would be the most efficient use of energy in buildings. Different individuals have very different requirements for health, comfort and efficient performance—the three ascending levels of the human criteria hierarchy. Symptoms of ill health and discomfort have powerful effects on the efficiency with which work can be performed in schools and offices, so even a narrow economic focus requires that indoor environmental effects at all three levels be considered.

The national economic interest would best and most rapidly be served by the establishment of a virtual institute to actively apply and orchestrate three very different lines of research to establish the viability of any proposed solution to the conflict between energy conservation and productivity: (1) scientific studies of the chain of cause and effect at all three levels of the above hierarchy; (2) engineering development of innovative solutions; and (3) solution-oriented field intervention research in schools and offices, with users in the loop. Current practice is to start at (1) with a scientific breakthrough in the laboratory, proceed to (2) with engineering development of viable products, substituting marketing for (3). This is a slow, expensive and uphill road to follow. Scientific understanding has often followed engineering optimization of solutions that emerged empirically in the field. The advantage of reverse-flow field-to-laboratory development is that it provides the "pull" that is needed to develop

[1]Note that the contents present the views of their authors, not necessarily those of the Department of Energy, RAND, or any other organization with which the authors may be affiliated.

successful products. A field trial of an innovative solution creates facts that must be scientifically explained, such as why it did or did not work, and if it did, justifies engineering effort and a subsequent return to the field to demonstrate in a wider context the applicability of the scientific explanation and the acceptability of the engineering solution. A national "IEQ Institute" would take an entrepreneurial approach to the introduction of new solutions.

In this paper, a range of potentially very effective solutions to the conflict between energy conservation and productivity are proposed. They have synergy, in the sense that they work towards the same end and would work very well together, but the claim that they would help to solve the conflict is sometimes based on experience and insight rather than on established facts. Some represent a "technological fix" that users would not even notice, while others affect users noticeably. In both cases, the field-to-laboratory approach would advance knowledge and accelerate the "idea-to-widespread adoption" process while ensuring rapid failure of ideas that either do not work or would be unacceptable to users even if they did work. A technological fix of the problem should include pollution source strength reduction by selection of materials and by point exhaust, increased ventilation rates using energy recovery from exhaust air, and efficient sub-micron filtration to remove respirable airborne particles. Users must be involved in solutions involving energy storage in the building structure and in solutions requiring user empowerment, such as individual control of microclimate, redistribution of energy between individual microclimates, openable windows, natural ventilation and closed-loop building operation with users in the loop. In all of these cases, field intervention experiments by the proposed IEQ Institute would be an appropriate first step.

Some key concepts discussed in this paper

- IEQ (Indoor Environmental Quality): Temperature, IAQ, humidity, draft, noise, lighting, daylighting, space, etc.
- IAQ (Indoor Air Quality): Gaseous and particulate metrics of air pollution.
- PAQ (Perceived Air Quality): Based on subjective judgments of the acceptability of odor and irritation effects.
- The Human Criteria Hierarchy for indoor environmental effects on people: Health, comfort & performance (in ascending order) must all be considered, as the limiting criterion may be found at any level of this hierarchy.
- The 3.I principle of User Empowerment:
- Insight, Information and Influence are all essential if learning is to take place.
- The Idea-to-Widespread Adoption process:

1. Scientific studies to establish cause and effect
2. Engineering optimization
3. Field intervention trials of applicability and acceptability

- Energy conservation or productivity?

The problem addressed in this paper is the conflict between the undoubted need to reduce energy use in buildings and the reasonable economic requirement that energy conservation initiatives should not impact indoor environmental quality in offices and schools in such a way as to cause negative effects on productivity. The bulk of the energy used in offices and schools is for ventilation and thermal conditioning. It is therefore logical to begin by documenting the extent to which productivity is affected by air quality and by temperature.

Indoor Air Quality Effects on Productivity

Recent research at the International Centre for Indoor Environment & Energy in Denmark has demonstrated conclusively and for the first time that the efficiency with which office work can be performed is decreased by poor air quality (Wargocki et al. 2000a). In three independent experiments in real offices, removing a source of pollution (Wargocki et al. 1999, Lagercrantz et al. 2000) and increasing the supply of outside air when the same source of the air pollution, a well-used carpet taken from an office, was always present (Wargocki et al. 2000b) have both been shown to significantly increase the objectively measured performance of simulated office tasks. The subjects did not know the ventilation rate or whether the source was present behind a screen. Each exposure lasted almost five hours and the subjects were young women. The tasks included typing text onto a computer screen, numerical calculation, proof-reading text and responding in their own words to open-ended questions. They thus represent a cross-section of the tasks that are commonly performed in offices and schools, and may confidently be claimed to predict the likely effect of air quality on productivity in these types of building.

The mechanism by which performance was reduced is believed to be the inducement of several Sick Building Syndrome symptoms such as headache and fatigue, as the subjectively reported intensity of such symptoms was significantly affected by the exposures, and in the expected direction. Field studies have shown that SBS symptoms of this kind are more prevalent in poorly ventilated rooms, as indicated by measured CO_2 levels during occupation (Apte et al. 2000). Exactly how this occurs and what aspects of indoor air chemistry are involved is not known. The observed effects on performance are large enough to be

economically significant—a 6.5% decrease in performance in indoor air that was no more than realistically polluted, in comparison with indoor air that was unpolluted by the carpet but still polluted by bioeffluents from six occupants, all using VDUs that are themselves believed to be a source of indoor air pollution, as discussed in later sections of this paper.

Prior to these experiments, the prevalent belief among indoor environment professionals was that while poor indoor air quality might reduce productivity by affecting health and thus absenteeism, there were no direct effects on productivity (Fisk & Rosenfeld 1997). This view can be traced back to experiments by the New York State Commission on Ventilation (1923), in which no effects on typing or other simulated office tasks could be shown even when ventilation rates were reduced so that CO_2 levels reached 5000 ppm. These negative results seem likely to have dissuaded other researchers from undertaking experiments to demonstrate effects of air quality on performance at the much higher levels of outside air ventilation rate which occur in modern offices and schools. However, Nunes et al. (1993) showed that Canadian office workers reporting Sick Building Syndrome (SBS) symptoms performed computerized diagnostic tests less well than did subjects reporting no SBS symptoms, and Myhrvold et al. (1996) showed that Norwegian school children performed a diagnostic test of mental performance less well in classrooms with lower air change rates.

The most recent experiment cited above (Wargocki et al. 2000b) provides reliable evidence that increasing the outdoor air supply rate from the 3.0 Liters/second /person that is typical of home offices, to the 10.0 L/s/p that is now recommended for commercial office buildings in most countries would significantly improve the performance of office work. A further improvement occurred when the outdoor air supply rate was increased to 30 L/s/p. The quantitative relationship was a 1.8% increase in performance for each two-fold increase in the outdoor air supply rate expressed per unit of pollution load (i.e. per person or per olf) over this range, or a 1.6% increase in performance for each two-fold decrease in pollution load. On a national scale, assuming there are 95 million full-time workers paid an average of $36k per year in the USA, a two-fold increase in ventilation would cause an increase in performance worth $61.6 billion per year. Against this saving must be set the running costs for conditioning the additional outside air used to increase the ventilation rate. At least part of the benefit of improving the ventilation is the removal of airborne particles. Supply air filtration performs this function in systems with recirculation, but filters in themselves may be a source of airborne particles (Croxford et al. 2000). Replacing a used supply air filter with a clean one was

shown by Wyon et al. (2000) to cause office workers to feel better and also to improve their self-estimated productivity by 5.7%. The use of air cleaners to remove airborne particulates in schools and offices is suggested in a subsequent section of the present paper.

Milton et al. (2000) will show in a forthcoming paper that the risk of sick leave was significantly associated with local rates of ventilation in a large enterprise employing 3720 people in Massachusetts, USA. The relative risk of short-term sick leave was 1.5 among the 600 office workers. The mechanism for this effect is believed to be the increased cross infection that occurs at low outdoor air supply rates, particularly for upper respiratory tract (URT) infections. Increased ventilation lowers the density of airborne bacteria and virus molecules. Sick leave constitutes a cost on any enterprise and thus reduces productivity. Without assuming any effect of the increased URT infection rate on the performance of employees who are not absent on sick leave, the authors calculate that net savings of $400 per employee would result from improving outdoor ventilation rates from 12 to 24 L/s/person, yielding annual savings of $22.8 billion per year on a national scale in the USA. National savings of $6 to $16 billion annually had been predicted by Fisk and Rosenfeld (1997) on the basis of earlier studies of cross-infection rates for URT at different ventilation rates, making conservative assumptions. It should be noted that these savings due to reduced sick leave for URT infections would be in addition to the direct effect of increased ventilation on performance that was estimated above.

Thermal Effects on Productivity

Personal experience is sufficient to convince most people that it is difficult to study or perform office work effectively when it is even slightly too hot or too cold. That there is a direct effect of the thermal environment on mental work is supported by a wealth of published experimental results, extensively reviewed by Wyon (1993, 1994, 1996a) and by Fisk and Rosenfeld (1997), who have conservatively estimated that improving the thermal environment in US office buildings would result in a direct increase in productivity of 0.5% to 5%, worth $12 to $125 billion annually. While the distracting effect of thermal discomfort is obvious, other thermal effects in offices and schools are equally important but not intuitively obvious or perceptible by personal experience, as discussed below.

Many symptoms of environmentally induced distress, including many that are conventionally included in the Sick Building Syndrome, are experienced more intensively at mildly elevated temperatures, even within the range providing

thermal comfort for more than 80% of the population, i.e. 20-24 C (68-75 F). The effect has been reported in several field intervention experiments (Krogstad et al. 1991, Mendell et al. 1999) but is not apparent in cross-sectional studies, most probably because indoor temperatures change continuously—they are not a permanent characteristic of a given indoor volume. By exacerbating SBS symptoms, elevated indoor temperatures can have an additional, indirect effect on school and office productivity.

Perceived air quality is much lower at moderately raised indoor temperatures and humidities (Fang et al. 1999). A change from 18 C and dry to 28 C and humid can increase the proportion dissatisfied from 10% to 90%, and the thermal effect is greater for clean air than for normally polluted indoor air. It has been shown in field intervention experiments that the performance of office work decreases by 1.5% for every increase by 10% in the percentage dissatisfied with indoor air quality (Wargocki et al. 2000b), and although the experiments on which this estimate is based involved manipulating pollution sources or ventilation rates, not temperature or humidity, it is quite possible that thermal effects on perceived air quality (PAQ) constitute a further mechanism by which thermal effects on productivity may be occurring.

There are large individual differences in preferred air temperature, as much as 10 K (= 18 F degrees) in standard clothing. Wyon (1996b) reviewed estimates of inter-individual variation in neutral temperature and estimated that individual control of 3 K about the group average neutral temperature, i.e. a range of 6 K (= 11 F degrees) would be necessary for 99% of office workers in their preferred clothing to achieve thermal neutrality. People use clothing adaptively to compensate for individual differences if they are allowed to do so. Individual differences are lower when no dress code is in effect, as people who have a low neutral temperature tend to dress lightly, and vice versa, up to the limits imposed by convention and decency. Altering clothing insulation is a rapid and effective means of altering the whole-body rate of heat loss to the environment by a few multiples of 10 watts, which is sufficient to adjust for most individual differences, but conventional clothing is unevenly distributed over the body surface and adjustment of the insulation value often results in "thermal asymmetry", i.e. some parts of the body being too cold, while others are too hot. This is not always acceptable. The development of clothing that could more easily and comfortably adjust to a range of room temperatures would contribute enormously to energy conservation in buildings, assuming that users were in the control loop, as discussed in later sections. The thermal insulation of seating can also be used adaptively, and should be regarded as an additional clothing item.

Productivity is reduced when many individuals have to occupy the same indoor volume with no individual means of adjusting the temperature they experience, as thermal effects progressively reduce the performance of those whose neutral temperature is not exactly equal to the group average—the neutral temperatures of 40% of any group of office workers differ by at least 1 K (1.8 F degrees) from the group average, while those of 9% differ by at least 2 K (3.6 F degrees). Wyon (1996b) has estimated that individual control equivalent to being able to select air temperature in a 4 K range (plus or minus 2 K, or 3.6 F degrees) would lead to an increase of about 3% in the performance of both logical thinking and very skilled manual work, and to a 7% increase in typing performance, relative to performance maintained at the group-average neutral temperature. Tsusuki et al. (1999) have recently shown that desk-mounted devices are easily capable of providing this degree of individual control. The advantage of controlling the microclimate is that it can be achieved in minutes with only about 100 watts of installed power per person, whereas controlling room temperature requires about 1000 watts of power per person and can still take hours. The rate of metabolic heat production per person is about 100 watts, and the time constant of the body is 20-30 minutes. Microclimate control is better matched to this human scale than is room temperature control.

There are many reasons why individuals differ in terms of preferred air temperature, the thermal parameter that is most often controlled by HVAC systems in the US, followed by humidity. The most influential individual differences are in the rate of metabolic heat production, which is largely determined by activity, and in clothing insulation and vapor diffusion resistance, as discussed above. Age and gender differences in these factors can lead to systematic differences in thermal preference between groups, but in real buildings as opposed to laboratories, the variance between occasions for the same person is as large as the variance between randomly selected individuals (McIntyre 1980). This is more because activity and clothing may differ between occasions than because subjective preference is unstable. Humidity, air velocity and thermal radiation exchange with hot or cold surfaces that are close to a person will obviously bias preference for air temperature, and these may differ spatially within a building as well as over time. Desk-mounted devices usually provide individual control of thermal comfort by altering air velocity and surface temperatures close to a person, as this can be done without affecting other occupants of the same space, while air temperature differences induced locally will rapidly have an effect on the rest of the space.

Energy Efficiency

HVAC systems in conventional buildings provide thermal background conditions of air temperature and humidity and are designed to maintain these factors as uniformly constant as possible within each control zone, which may be a whole floor of a multistory building with several hundred occupants. The set points for different zones are in principle the same. Division into zones is to reject the influence of external disturbances, such as solar gain, and internal disturbances, such as changing lighting power or occupancy, which may be expected to differ systematically between zones. Although large amounts of energy are used to maintain air temperature and humidity at the set points in each zone, these represent crude approximations to the thermal conditions that would most enhance individual health, comfort and productivity. As the ultimate purpose of using energy in buildings is not to maintain conditions as close as possible to set points, but to enhance the health, comfort and productivity of the occupants, current practice is not an efficient use of energy.

The same is true of air quality. Individual differences in sensitivity to air pollution are much larger than individual differences in thermal preference. This is true for sensitivity to inorganic gaseous and particulate materials in indoor air and particularly true for sensitivity to allergens, which are usually organic. Both inorganic and organic air pollution can enter with outdoor air or originate from indoor sources such as building materials, mold or bacterial growth. Hyper-sensitive individuals may have thresholds of sensitivity—the airborne pollution concentration that will cause irritation—that are 100 000 times lower than those of normally healthy people, and people who have developed true allergies may have thresholds of sensitivity 10 times lower than this (SOU 1989). It is believed that repeated exposure to allergens can lower thresholds of sensitivity, leading to the development of allergic symptoms where none occurred before, so it is important for all occupants, not just for particularly sensitive individuals, to maintain good IAQ, with low concentrations of gaseous and airborne particulate pollution. The traditional approach is to ventilate indoor spaces with large volumes of outside air. While in modern offices and in cool weather this can sometimes serve to remove excess heat and thus to reduce the cooling load and save energy that would otherwise have to be used for this purpose, so that maintaining good IAQ is "free", during hot weather thermally conditioning the outdoor air flow required to maintain acceptable IAQ represents the largest use of energy in buildings. Proof that IAQ affects productivity provides an economic justification for using energy to maintain acceptable IAQ, but energy conservation goals mean that more efficient ways of doing so will have to be

developed. Compromising health and productivity to save energy is both unimaginative and unacceptable.

In the following sections some new ways of enhancing productivity in school and office buildings while reducing the energy used to optimize thermal and IAQ conditions for their occupants will be introduced. Technical improvements in the efficiency with which energy is used to meet conventional HVAC goals, such as more efficient compressors or better insulation, will not be addressed.

Technological Fix Solutions

Conserving energy by means which do not affect health, comfort or productivity, do not alter occupant behavior and in the ideal case are not even be noticed by occupants, is popularly called a "technological fix". The following solutions come under this heading.

Pollution Source Strength Reduction

International ventilation standards of minimum ventilation are in the process of being altered to take account of the fact that the flow of outside air must not only remove bioeffluents generated by the occupants, but also other forms of air pollution originating from indoor sources. The source strength of non-human sources of indoor air pollution, in terms of their contribution to degrading perceived air quality (PAQ), may exceed that of the occupants (Fanger 1988). Their source strength in terms of how they affect health and productivity may be greater still, as bioeffluents are considerably less toxic and irritating than the other air pollutants found in indoor air. The energy used to condition the outside air that is needed to dilute and remove air pollution from these other sources can be radically reduced by selecting materials with low emission. This applies not only to building materials, but also to furnishing materials such as floor and wall surfacing, carpets, rugs and curtains, and to equipment such as business machines. At present, manufacturers in some countries can voluntarily submit samples of their products for emission testing with respect to PAQ, and architects are encouraged to select materials found to have low emission by using this criterion, but there is no legal obligation for manufacturers to document emissions or for architects to take account of them. If selection of materials with a low impact on PAQ would increase the first cost of a building, only clients with a long-term interest in the running cost are likely to follow this good practice. Field trials which document the impact of materials selection on HVAC costs, the acceptability of low-emitting materials to occupants and the additional economic benefit in terms of the impact of better IAQ on health and productivity are

urgently required before this potentially huge new avenue for energy conservation can be properly exploited. Augustin and Black (2000) report on a workshop at the recent conference "Healthy Buildings 2000" which dealt with current labeling schemes for materials emissions, but even this group did not deal with evaluating the benefits of materials selection for energy conservation in buildings or the likely impact on health and productivity. In view of the very large energy savings which could result, with nothing but benefits for health, comfort and productivity, this whole area should be a high priority for DOE-funded R&D, deployment initiatives, demonstration projects and validation.

Point Exhaust

That air pollutants should be removed at source wherever possible is the basis for materials emission testing and materials selection. Where the source must be physically present in a building for some reason, the principle still applies. Point exhaust is routinely used in industrial buildings to remove dust and fumes at their source, in fume cabinets in chemical laboratories and even in operating rooms in hospitals, to reduce the exposure of operating room staff to the anaesthetic gases administered to the patient, but not in schools or offices. This represents another massive opportunity for energy conservation, as follows.

Office machinery such as copiers and laser printers are sources of volatile organic compounds and ozone, which are now known to react with each other to form more aggressive but short-lived daughter products in indoor air (Wolkoff et al. 1993, Wolkoff 1995, Knudsen et al. 2000, Lam & Lee 2000). The hot components in all electronic equipment such as PCs and other types of printer are coated with flame retardants which are emitted when the equipment is operated, at a rate which is highest in new equipment. The most commonly used flame retardant chemicals, organophosphates and polybrominated compounds, are extremely toxic and have been shown to be pervasively present in samples of office dust (Pardemann & Salthammar 2000). All electronic equipment, whether or not it needs a fan, takes in room air for cooling temperature-sensitive components. Room air contains airborne dust, which is deposited on the component boards and is heated to temperatures well above 70 C (158 F) when the equipment is operated. Dust which is heated above 70 C undergoes three changes: it becomes more finely divided and dry, it emits the air pollutants it has absorbed, and it becomes a source of unpleasant odor (Hirvonen et al. 1990). These changes, particularly the increase in the number of sub-micron and therefore respirable particles, have been shown to significantly reduce lung function (Raunemaa & Sammaljärvi 1993). It is clear from the above that the air which has entered the casing of electronic equipment, and particularly copiers and laser printers,

represents a source of air pollution, is not fit to breathe and should leave the building as rapidly as possible. Point exhaust from the casing of all electronic equipment would achieve this, and it would also remove the heat they generate, which amounts in offices to at least as much as is generated by occupants (100 W per occupant). Removing it at source would have several beneficial effects: 1) it would reduce the cooling load on the building, by an amount many times larger than the energy required for the point exhaust system; 2) it would raise supply air temperatures, eliminating complaints of draft; 3) historic buildings which cannot be used as modern offices because their cooling and ventilation capacity is not able to deal with larger heat loads than occupants plus lighting could be brought into use again as offices; and 4) the exhaust air flow would be very suitable for energy recovery and preheating of outside air, as it will be well above room temperature. Field experiments to demonstrate and validate the usefulness of point exhaust are required.

Energy Recovery from Exhaust Air

Whenever the temperature or humidity of the exhaust air rejected from an office or school differs from that of outside air, it represents an in-house energy source that is currently underused. In the simplest case it could be used in counter-current heat exchangers to condition the incoming supply air, utilizing even the latent heat of more humid air by allowing outgoing moisture in warm air to condense on conducting surfaces separating incoming from outgoing air. This can be done centrally, zone-by-zone or even room-by-room. Counter-current heat exchangers have no moving parts and are extremely cheap to install and run. They work well in summer and in winter. They are applicable in the simplest classroom and would permit greatly increased ventilation rates at a very low first cost. They would pay for themselves very quickly in terms of reduced running costs. The reason they are not used may simply be that they are low-tech and the profit margin on them would therefore be very small. They do not impact the occupant in any way.

Heat pumps can be used to alter the temperature of the energy flow that is recovered from exhaust air. By this means the recovered energy can be used for other purposes than conditioning incoming outside air, e.g. to heat hot running water or to heat or cool the water circulating in radiant heating or cooling systems. Heat pumps similar to the ones in domestic refrigerators can be mass-produced at a very low unit cost and are suitable for distributed use in buildings, where they can recover energy from exhaust air and either use it immediately or store it as described. Large heat pumps located in the central HVAC plant room are more expensive but also more efficient. In Sweden energy recovery from

exhaust air is mandatory in all buildings except in dwellings with two or fewer apartments. A typical apartment building easily recovers enough heat from exhaust air to heat all the hot water that is used by the occupants. In schools and offices too little hot water is required for this to be the sole repository of the recovered energy. Low temperature heating and cooling systems in which the floors, ceilings or walls are heated or cooled represent the perfect repository for this kind of recovered energy (Olesen & Petras 2000). In winter they raise the radiant temperature and make it possible to achieve thermal comfort at a lower air temperature. This increases the perceived air quality, as demonstrated by Fang et al. (1999), saving more energy by reducing the outside air flow required to provide subjectively acceptable air quality when this is the dimensioning criterion for the ventilation rate, as is most often the case. In summer they are used for radiant cooling.

Heat recovery systems and low-temperature radiant systems are already available, but unbiased field experiments to demonstrate their effectiveness are required.

Air Cleaners

Air cleaning devices can remove airborne particles from room air, delivering clean room air at a fraction of the energy cost of using outside air, since room air is already conditioned. Electrostatically-enhanced air cleaners have high rates of efficiency in the sub-micron region, retaining particles small enough to pass straight through the nose. They do not have the high fan power and unacceptable noise levels of conventional HEPA filter units. Free-standing units of this kind have been shown to reduce airborne particle density in working offices (Croxford et al. 2000) and to reduce nasal congestion (Skyberg et al. 2000). There is no reason why air cleaners could not become an integral part of office design, graduating from the status of appliance to that of system component. Ventilation air will still be required to remove heat, CO_2 and other gas-phase pollutants, and to provide oxygen, and it will still need to be filtered to remove particles originating outside, but air cleaners can greatly reduce the amount of outside air required for the purpose of removing airborne particles. Many different kinds of air cleaner are available, but unbiased field experiments to determine and demonstrate their relative advantages are required.

Solutions That Affect Building Occupants

The "technological fix" solutions discussed above do not inconvenience users and will conserve energy, but they also involve a modest increase in the first cost

or retrofit cost of a building. These increased costs can be recovered over time from the reduced running costs. They are economically justifiable over the complete life-cycle of a building, but if first cost is an insuperable barrier, energy conserving strategies which involve occupants and may inconvenience some of them must also be considered. A number of solutions of this kind are discussed below.

Energy Storage in the Building Structure

Energy can be very effectively conserved at no first cost by storing it in the building structure, transferring heating or cooling power that is available cheaply or free in one period to another when it is needed but would be more expensive, e.g. by using night air to cool the building structure and so reduce the amount of active cooling required during the day, or by allowing a building to warm up during the day to reduce the energy required for heating it at night. Cheap off-peak energy can be stored in the same way. Energy storage is such a cost-effective means of conserving energy that it is becoming economically justified to install and run water or ice storage systems as components of the HVAC system, even though they are huge, costly and complex to run. Energy storage in the building structure has been used throughout history because it is has none of these disadvantages, but it is now regarded as unacceptable because it does inconvenience occupants to some extent—room temperatures cannot be maintained exactly constant and this results in increased complaints. It is very likely that a compromise between energy conservation by this means and thermal discomfort is acceptable under some conditions, but it will be necessary to demonstrate in field experiments that this is so before building controls can be reprogrammed to conserve energy at virtually zero first cost.

Solar energy can be stored in the building structure over a 24-hour cycle. Architects have traditionally used this possibility at the expense of maintaining thermal comfort, and in recent years have increasingly begun to use heavy internal walls and floors exposed to solar gain as passive heat storage components, often in spaces such as corridors or atria that are occupied only intermittently. Radiant heat exchange with occupants close to these walls or floors is always increased, and without expensive means of distributing the heat throughout the building, air temperatures will also be higher, resulting in thermal discomfort in the heat of the day. In buildings with raised floor ventilation, the load-bearing floor below can be used to store energy by causing it to become hotter or colder than room temperature. This does not affect the radiant temperature experienced by the occupants but will inevitably affect supply air temperatures at some points in the storage and recovery cycle.

Workstation-mounted devices that permit some degree of individual control of the microclimate experienced by each occupant can increase the range of acceptable supply air temperatures. They are discussed in the following section.

Individual Control

Simple devices at each work station can alter the thermal environment experienced by each occupant, compensating for air temperatures that are too high by raising the air velocity, thus increasing convective cooling, and compensating for air temperatures that are too low by locally raising the radiant temperature. Tsusuki et al. (1999) have shown that such devices can maintain thermally comfortable conditions over a considerable range of air temperature. Their primary purpose is to permit individuals with widely different thermal requirements to be thermally comfortable at the same room air temperature, but they are also an effective means of maintaining thermal comfort when room air temperature is above or below what would be ideal at any given time. They are thus a key factor in making it acceptable to store energy in the building structure as described in the previous section.

Wyon (1996b) has shown that individual control of the thermal microclimate can increase productivity by a considerable amount even when the room air temperature is at the group average neutral temperature, and still more when it is below or above. Given that this is desirable, the additional energy used to achieve individual control would be greatly reduced if individual work station units could transfer energy between them, occupants who were too hot transferring heat to those who were too cold, and vice versa. This could be achieved by using small heat pumps to cool or heat the air that is delivered to each work station, linking them together by means of a circulating energy transport medium that might be either water or air. The net energy requirement is zero when the air temperature is equal to the group average neutral temperature, and consists only of transfer losses—a zero-sum energy deployment to achieve 100% thermal comfort instead of the usual 80% in conventional buildings. If air temperatures were permitted to rise in one part of a zone to conserve energy in the building structure, e.g. by deliberately allowing solar gain to affect air and radiant temperatures on one side of a building, energy transfer between work stations would be an effective way of cooling the occupants affected by solar gain while heating the occupants who were unaffected, with no additional energy input except to compensate for transfer losses when the building was in cooling mode overall. Transfer losses become heat, reducing the heating required when the building is in heating mode. A system of this kind

could easily be constructed. Field experiments to demonstrate applicability and acceptability would be required.

User Empowerment

Individual control of the microclimate at each workstation is a form of user empowerment. As described above, each user can utilize the cooling or heating power that has been delegated to the workstation unit, and the only compromise involved is that background conditions will not always be ideal for every user. This is the normal situation in conventional buildings for all users except those who happen to have thermal requirements equal to the set temperature. Energy-conserving solutions that store energy in the building structure and result in cyclical changes in the set temperature can thus be deployed with very little impact on any individual. With energy transfer between workstations, users do not need to consider the energy consequences of exercising their preference, but this is not always the case. In the following sections, openable windows and natural ventilation require user empowerment, and user choices have a direct effect on energy conservation. It is therefore necessary to consider whether it is energy-efficient to empower users to this extent.

The purpose of most of the energy used in buildings is to improve environmental conditions for users. This process is only energy efficient if it promotes user health, comfort and productivity, whether or not it achieves the usual engineering goals of maintaining constant indoor environmental conditions. As user requirements depend on task demands and on user activity, fatigue and health, all quantities that change from minute to minute, only the users themselves can respond to them to continuously optimize energy use. Anything else is a gross approximation and so inefficient. It is thus axiomatic that "Empowerment Enables Energy Efficiency", although most building operators will claim the reverse.

This "4.E" axiom will only result in energy conservation when users are properly motivated and informed. As in all cases where learning must take place, the 3.I Principle applies: users must be given sufficient Insight, Information and Influence. Providing any two of these will fail to ensure that learning can take place. For example, users with insight and influence but no information cannot respond intelligently, while users with insight and information but no influence cannot respond at all. A good illustration of these two unsatisfactory situations is in learning to play darts. i.e. being unable to see the board or having no darts. Insight into how to throw darts and how the scoring system works is similarly essential for success. Insight in the case of a building user is an understanding of

how the building HVAC system works and which actions would conserve energy. Information is continuous feedback on relevant indoor and outdoor conditions, on what the HVAC system is doing right now and the current rate of energy use. Influence might consist of an openable window, a personal heating or cooling system, a personal air supply that can be increased or decreased, perhaps equipped with personal supply air filtration, a list of telephone contact numbers to HVAC operations personnel, or a two-way Internet connection to the HVAC system and its operators. Users in conventional buildings have none of these essentials, not even a handbook, a thermometer or access to a thermostat.

The Center for the Built Environment (CBE), established 1997 at the University of California, Berkeley (UCB) by the NSF has developed an Internet home-page linked to a building's HVAC system that can provide both Information and Influence. Users can obtain on-line information from the building system and alter their recorded preferences. Field experiments in which short courses for building users provide a degree of Insight are required to demonstrate how the 4.E axiom and the 3.I Principle apply to building occupants.

Openable Windows

Building occupants are very keen on openable windows, for a wide variety of reasons, some practical, some psychological. They are prepared to put up with considerable disadvantages to retain the advantages, one of which is that they represent user empowerment. Their feasibility is obviously dependent on the meteorological climate and on local air quality and noise conditions. They are much more common in Europe than in the USA, and ways are currently being found to integrate openable windows with modern energy-efficient indoor climate control systems. In the simplest case, the system detects an open window and immediately ceases to ventilate, heat or cool the volume affected, effectively delegating control to the user who opened the window. If this action provides conditions that enhance the users' health, comfort and productivity, and also prevents energy being used to condition that part of the building, it was clearly energy-efficient. However, if users leave a window open onto an empty room, this may not be the case. The control system must monitor occupancy as well as open windows, environmental conditions and energy use in order to respond effectively. Field experiments are required to develop ways of doing so and to determine whether openable windows do conserve energy.

Natural Ventilation

Naturally ventilated office and school buildings are currently being constructed in Europe. Not all of them involve openable windows. Many of them are hybrid buildings which utilize natural ventilation when weather conditions permit, and conventional HVAC systems when they do not. Natural ventilation is only possible if building occupants are able to accept some compromises, e.g. it is quiet but it cannot provide supply air filtration, and as ventilation rates and internal temperatures are affected by wind, sun and the external temperature, users must accept this either as an advantage, as many do, or as a compromise that is acceptable to achieve energy conservation. Many parts of the USA have temperate climates comparable to or better than those of European countries. Field experiments to demonstrate the advantages and disadvantages of natural ventilation in different regions of the USA are required.

Closed-Loop Building Operation

Conventional building control systems are open-loop with respect to the target dependent variables of health, comfort and productivity. They control room temperatures and sometimes humidity but there is no feedback from occupants. This obviously has the potential for being very energy inefficient if the room temperatures and the humidity do not correspond to occupant requirements at the individual level. Massive amounts of energy are currently used to condition empty rooms, to heat occupants who are too hot, cool them when they are already too cold, and alter humidity levels to which they are insensitive. Feedback from occupants is necessary to avoid these wasteful practices. Information on occupancy can be obtained from movement sensors already built into many desk-mounted TACs (Task/Ambient Conditioning systems for individual control of the microclimate), or from CO_2 sensors in the exhaust air from each zone. Information on occupant requirements can be obtained from user interfaces of the kind developed by CBE and described above. On a longer time scale, the Occupant Satisfaction Survey developed by the CBE and administered over the Internet can provide feedback on all building operations, including lighting, cleaning and maintenance. Field experiments to demonstrate how these new possibilities can benefit energy conservation are required.

Leveraging Foreign Investment in Research

In the preceding sections some concrete proposals for new research on energy conservation in buildings as it affects occupants have been described. It will not

always be possible to quantify the effects on health, comfort and productivity, but field studies of the solutions proposed should move in these directions. In 1998 a new research center for this kind of research was set up in Denmark—the International Centre for Indoor Environment and Energy (ICIE, from the Danish "Internationale Center for Indeklima og Energi"). Situated in the Energy Engineering Department of the Technical University of Denmark and based on a group of researchers with an established international reputation for research on thermal comfort and perceived air quality under Professor P.O. Fanger, who currently serves as the first Director of ICIE, the initiative will be supported for 10 years by the Danish National Science and Technology Research Council (STVF). The proposal to perform the research necessary to reconcile the requirements of energy conservation with those of building occupants was one of 40 competing proposals to establish an international center of excellence in engineering research and development. It was selected for generous support because energy conservation measures in buildings are known to have led to negative consequences for health, comfort and productivity, while conventional measures to improve indoor environmental quality in buildings, e.g. by increasing the ventilation rate, almost always increase energy use. The research currently being undertaken at the ICIE is multidisciplinary, involving experts in building, HVAC, and indoor air chemistry as well as experts in human health, comfort and performance assessment. It is carried out in advanced climate chambers, in simulated offices, and in the field. The findings are not always transferable to US buildings.

It is therefore proposed that a similar research initiative should be taken in the US. It could be a "virtual institute" rather than a bricks-and-mortar institute. The "IEQ Institute" would apply the ICIE approach to new and existing US buildings. This would be the most rapid and cost-effective way to ensure that future energy restrictions have no negative consequences for the health, comfort and productivity of the US population. The solutions outlined in this paper would be candidates for research at the new IEQ Institute. However, its brief should not simply be to undertake research, but to expedite the development of successful solutions, from idea to widespread adoption, as set out below.

Expediting the "Idea-to-Widespread Adoption" Process

There are three essential elements in developing effective solutions to the conflict between energy conservation and user requirements:

1. Scientific studies to establish cause and effect;
2. Engineering optimization;

3. Field intervention trials of applicability and acceptability.

Current practice is to start at (1) with a scientific breakthrough in the laboratory, proceed to (2) with engineering development of viable products, substituting marketing for (3). This is a slow, expensive and uphill road to follow, and in the history of science, scientific understanding has often followed rather than preceded engineering optimization of solutions that had emerged empirically in the field. The advantage of departing from the conventional sequence is that it provides the "pull" that is needed to develop successful products. A field trial of the prototype of an innovative solution creates facts that must be scientifically explained, such as why it did or did not work, and if it did, justifies engineering effort and a subsequent return to the field to demonstrate in a wider context the applicability of the scientific explanation and the acceptability of a properly engineered solution. The IEQ Institute would be able to expedite the process by iteratively applying all three stages, in the appropriate order. The research would be contracted out to national laboratories such as National Renewable Energy Laboratory, Oak Ridge, and Lawrence Berkeley National Laboratory, to university research centers, and to private industry, depending on the capability, experience and equipment required for each aspect of the work.

Existing centers for scientific research have no brief to optimize the engineering of proposed solutions, which is essential if ideas are to become reality. This is left to the private sector, which likes to market new solutions as if they were based on science but seldom funds scientific research worth the name or undertakes properly-controlled field intervention studies in schools and offices to determine whether a new solution conserves more energy than existing alternatives and is also acceptable to occupants. The process of taking an idea that would benefit the national energy economy all the way through to widespread adoption can be derailed by the omission of any one of these three stages. A nationally-funded IEQ Institute that was able to coordinate multidisciplinary research and development would serve the public interest by taking an entrepreneurial approach to the introduction of new solutions. Royalties would be earned by protecting the intellectual property that is developed at the engineering optimization stage of the idea-to-widespread-adoption process. Joint development agreements (JDAs) could make this stage in the process self-funding even if the preceding and following stages had to be funded by government to preserve impartiality in evaluating competing solutions. An IEQ Institute would pay for itself many times over in any national economic calculation.

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Conference Papers on Systems Approach to Energy Use

Promoting Renewable Energy and Demand-Side Management Through Emissions Trading Program Design

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Not regarded as paragons of consistency even at the best of times, some politicians quickly changed their tunes on electricity deregulation after a trying summer in which rolling brownouts and skyrocketing retail electricity prices in parts of California caused a public outcry amongst the unfortunate consumers who bore the brunt of those maladies. Where previously politicians had sung the virtues of competition amongst electricity generators, many in California and beyond have sounded a more wistful tune of late, calling into question the whole deregulation endeavor and recalling fondly the good ol' days of state regulation. In the search for causes of this summer's problems, those who would slow the pace of deregulation have managed to draw attention away from the most plausible explanation: that failure to deregulate quickly enough has led to a mismatch between consumers' demand for electricity and utilities' capacity to supply it. As economic growth continues to drive new electricity demand, similar problems may emerge in other deregulating states unless effective solutions can be found.

The conventional response to such supply shortages, namely increasing supply by building large new electricity-generating facilities is limited as a short-term solution by the length of time it takes to bring such facilities on-line. Moreover, in the long run this response grows less attractive when one considers the prospect of high fossil fuel prices and the additional air pollutant emissions that would result from a new wave of fossil-fired power plant construction.

Alternative approaches such as expanding renewable energy generation and managing energy demand tend to receive less attention but hold considerable

[1]Note that the contents present the views of their authors, not necessarily those of the Department of Energy, RAND, or any other organization with which the authors may be affiliated.

promise both as short-term fixes and long-term solutions. In the short-term, renewable energy generating units can be brought on-line relatively quickly since they tend to be smaller and more scalable than conventional plants. Because renewables do not require fossil fuel inputs for production, promotion of renewable generation also constitutes a sound long-term strategic means of reducing exposure to fuel-price fluctuations and oil market manipulation by the Organization of Petroleum Exporting Countries (OPEC). Moreover, renewable generation avoids liabilities associated with the onset of new and more aggressive air emissions regulations aimed at reducing harmful byproducts of combustion such as sulfur dioxide (SO_2), nitrogen oxides (NOx), greenhouse gases (GHGs), and others. Demand-side management efforts, which also mitigate the need for additional fossil-fired power generation, yield similar benefits.

Yet despite such benefits, market imperfections prevent these activities from being exploited to their socially optimal level. Public benefits such as greater national energy independence and improved air quality are difficult to account for using existing market pricing methods, and their use is non-excludable, making them susceptible to free-riderism, whereby some of those who enjoy those goods' benefits are not made to pay for them. A variety of government schemes, such as tax breaks and research subsidies, have been employed over the years to address these imperfections, with some success. A new trend amongst states towards Renewables Portfolio Standards, which mandate that a certain minimum percentage of states' total energy supply must be generated by renewables, may be particularly effective.

Another promising solution that deserves exploration alongside these other policy measures involves the integration of incentives for renewables generation and demand-side management within the context of emissions trading markets such as the US SO_2 Allowance Program and the emerging market for GHG emissions reductions. As emissions trading's popularity continues its rapid growth, so also can opportunities for promotion of renewable energy and demand-side management, which undoubtedly contribute to achievement of emissions trading programs' objectives. But this promise will only be realized if deficiencies in the design of existing trading programs can be rectified, if not within existing programs, then in emerging ones. In this paper, we examine some of these deficiencies and begin the process of formulating effective solutions.

Economics of Emissions Trading

The superiority of emissions trading programs over other air regulation methods derives largely from the compliance flexibility that sources enjoy relative to more

rigid "command-and-control" regulations. Whereas a command-and-control regulation might require, almost without regard for cost, installation of a particular abatement technology or achievement of an emissions reduction from a particular stack, sources affected by an emissions trading program have considerably more options by which to achieve compliance. In such programs, which to-date have been applied mostly to electricity generating facilities, affected sources need only prove that their emissions during a given compliance period did not exceed their holdings of valid emissions permits. Whether sources choose to achieve this balance by installing abatement technology, fuel-switching, by purchasing additional permits from another source, or some other environmentally-sound method is mostly unimportant to the regulatory authority.[2]

Profit-maximizing sources use this flexibility to choose the most cost-effective compliance method, enabling sources to reduce their individual costs of compliance as well as the system-wide costs of achieving a given environmental target, relative to command-and-control methods of regulation. In addition, the possibility of financial gain from selling surplus emissions permits to others creates an incentive to develop new, as-yet unknown methods of reducing emissions. This incentive for innovation further amplifies the cost savings that result from emissions trading, and enables air regulators to aim for more aggressive environmental targets than would otherwise be attainable. Unfortunately, however, economic incentives for emissions reduction are limited mainly to entities that directly produce emissions, even though additional cost-effective abatement options may depend on the activities of non-emitters such as renewables generators and electricity consumers.

Unequal Incentives

Renewable energy generation and demand-side management both contribute to air quality improvement (and a host of other benefits including some described above) by reducing the need for combustion of fossil fuels to generate electricity.[3] But the design of most existing emissions trading programs does not reward many potential investors who might undertake such activities, leading to under-investment and lost opportunities for cost-effective emissions reductions.

[2]Shifting production from an affected source to a production facility outside the bounds of the program is one example of a prohibited compliance method.

[3]This is true except where electricity is supplied largely by non-emitting means such as nuclear and hydro-electric generation.

Incentives do exist for owners of emissions sources that already fall under existing emissions trading regulations to invest in renewables and demand-side management. Such investments represent another way for sources to balance their actual emissions and permit holdings. For example, a utility might choose to displace some of its coal-fired generation by investing in a new wind-turbine. In doing so, the utility could maintain its supply of electricity while producing fewer emissions, effectively freeing up permits for sale to others or reducing the number of permits that it must acquire from others to achieve compliance. Likewise, investment in high-efficiency furnaces for residential electricity consumers can potentially benefit generators by helping to fulfill supply obligations without the need for emissions-producing new generation (though this is not likely to be regarded as a preferred means of achieving compliance[4]). Some emissions trading programs, such as the SO_2 Allowance Program, even offered additional incentives for affected sources to undertake such investments by offering bonus permits for certified investments in specified activities (see additional discussion below).

Comparable incentives are absent, however, for independent investors who do not own emissions sources affected by emissions trading restrictions. Independent renewables generators do benefit marginally from the existence of emissions trading programs to the extent that these place a price on emissions, and thus raise production costs for fossil-fuel generators with whom they compete. But an investment in wind-turbine electricity generation equivalent to the one described in the previous paragraph would, for an independent generator, free up no additional permits since non-emitting generators receives no allocation of permits in the first place. Moreover, no mechanisms exist for independent parties to stake legal claim to such permits. In fact, under some circumstances it is affected sources rather than independent investors who ultimately benefit, in a sense, from independent investments. Since renewables generation and demand-side management both provide an emissions-free way of reducing an electricity supply gap, affected emissions sources would benefit from avoiding the cost of acquiring additional permits to cover emissions resulting from new generation (though, it must be noted, they also forego the possibility of earning profits on that new generation).

[4]See Kirk Johnson, "Debate on Need for New Power Plants Ignores Conservation", *New York Times*, September 26, 2000.

Early Experience form Precompliance GHG Trading

In recognition of the environmental and economic successes of emissions trading markets in the United States, international negotiators of the Kyoto Protocol, an international treaty that would restrict GHG emissions from industrialized countries, have included three market mechanisms through which countries bound by the treaty could engage in trading to meet their national obligations. Following this lead, many national governments including those of the United Kingdom, Denmark, Germany, Canada, Australia, and others have proposed or are examining ways to establish domestic trading that would apply to sources within their respective countries. Considering the quantity of emissions reductions that will eventually be necessary to achieve the treaty's objective of preventing dangerous anthropogenic interference with the climate system, and the enormous cost of achieving these reductions without the cost-saving benefits of emissions trading, few would dispute that GHG trading has the potential, at least, to dwarf existing emissions trading markets and to provide incentives for massive flows of investment.

Despite the fact that few, if any GHG sources yet face legally-binding emissions restrictions, some companies have already begun to trade GHG emissions. In contrast to participants in existing legislated emissions trading markets, who trade legal authorizations to emit, participants in this "pre-compliance" emissions trading market exchange only "rights and data associated with verified emissions reductions that may constitute a claim against future compliance requirements". In other words, a seller transfers to a buyer ownership of the change in GHG emissions resulting from a specific activity, and this carries only a possibility, but not a guarantee, of government recognition under some future regulatory regime. Sellers view early trading as a way to monetize assets (i.e., emissions reductions) that would otherwise be valueless. Buyers view early trading as way to protect against unknown and potentially exorbitant compliance costs associated with future GHG emissions restrictions. Even after accounting for the possibility that some or all of the reductions they acquire may not be recognized by governments as a legitimate offset against their own emissions, buyers regard early trading as a worthwhile insurance policy.

Operating without firm trading guidance from governments, participants in pre-compliance GHG trading have mostly taken their cues from existing emissions markets to predict what sorts of emissions reductions have the highest probability of government recognition. Not surprisingly, would-be participants that invest independently in renewable energy generation and demand-side management face hurdles similar to those present in existing markets. In this context, the main impediment facing such investments can be thought of as a

problem of *ownership*, along with the related question of *quantification*. Given the enormous potential of GHG trading, it is particularly important that policymakers understand these problems so that a significant opportunity to create economic incentives for such valuable investments is not squandered. Moreover, it may be easiest to create such incentives in GHG emissions markets, whose rules are not yet written.

Ownership

Buyers in the pre-compliance GHG market typically only purchase emissions reductions that meet a somewhat standardized set of minimum criteria. These include, for example, requirements that reductions be "real," meaning that they resulted from a specific, identifiable activity, and that reductions be "surplus," meaning that the reductions are additional to any that might be required by existing law. Additionally, sellers must be able to adequately demonstrate legal ownership of the reductions they wish to sell. In the absence of clear ownership, a buyer may not be confident that a seller can legitimately transfer all legal rights to its reductions.

In many cases, ownership is not difficult to establish. For example, if an electric utility purchases a new technology that directly reduces its emissions, there is little doubt that rights to the resulting emissions reductions belong to the utility. However, when an activity results not in a direct emissions reduction from a particular process, but rather in a displacement of, or reduction in demand for, an emissions-producing process owned by another entity, ownership is less clear. For example, an owner of wind generation might claim an emissions reduction for having displaced existing coal-fired generation. But the existing generator or generators might claim to have generated the same reductions by purposely reducing fossil-fuel combustion, or by some other unspecified means. Knowing that in existing emissions trading markets affected sources generally need not explain nor justify the means by which compliance was achieved, and that determining the exact cause of fluctuations in emissions can be difficult, buyers are worried enough by such potential ownership disputes to avoid these types of reductions.

Quantification

Another essential characteristic of credible early GHG emissions reductions is that they be "measurable," or quantifiable by a replicable and transparent methodology. When a reduction is generated by directly changing emissions from a particular source, quantification can be simple. However, in the case of

renewables generation and demand-side management, quantification can be a significant challenge since the reductions being claimed from such activities actually occur on the site of the generator or generators whose electricity was displaced or consumed less. The challenge is to set an accurate baseline level of emissions that would otherwise have been emitted if the specified activity had not occurred. Establishment of this baseline requires accurate emissions data from existing generators, who may be reluctant to abet their competitors by delivering the requested data. If the data is somehow acquired, the reduction can be quantified by multiplying the quantity of electricity produced by renewables (or saved by demand-side management) by the baseline rate of emissions that would otherwise have occurred. The result is a quantity of emissions that can be offered for sale.

In a deregulated environment, calculation of baseline emissions rates against which to quantify reductions is complicated by the fact that several different utilities, each using several different generation technologies, might be producing the existing electricity supply. Since it would be impossible to determine exactly which generation technology produced particular electrons, a system average must be used instead. For this information, interested parties must rely on the Independent System Operator (ISO) that maintains the local grid.

To date, many buyers potential of reductions generated by renewables or demand-side management have demanded that the quantification methodology also use more than a static rate of emissions per electricity unit displaced or saved. In pursuit of a high degree of accuracy, buyers have demanded that claims of displacement or savings be measured against intra-day and seasonal variations in emissions rates. For example, a photo-voltaic solar generating unit that only produces power during daylight hours would have to measure emissions reductions against an emissions rate based on the mix of baseload and peaking units in use during those daylight hours, instead of the overall system average. Likewise, the quantity of emissions displaced by the photo-voltaic unit would change between seasons, as lower demand in the winter months might require less generation by relatively high-emitting peaking units than in summer months, when demand is high. Though buyers to-date have requested only that emissions data reflect intra-day and seasonal emissions rate variations, theoretically there is no limit to the level of detail at which emissions rate variations might be expressed.

Often such detailed information is unavailable, making quantification extremely difficult, and harming would-be sellers' chances of executing a transaction. Even

when such information is available, the amount of time and expertise necessary to undertake the appropriate calculations can deter prospective sellers.

Possible Solutions

Together, the preceding problems prevent some investors in renewables and demand-side management from earning revenue associated with GHG reductions and result in lower overall investment in such activities. Since pre-compliance trading is, by its very nature, undertaken only in preparation for eventual legislated emissions trading programs, it is not the pre-compliance market in particular that requires government solutions. Rather, as governments in the US and elsewhere ponder whether and how to design effective legislated emissions trading markets, they ought to consider what rules will maximize incentives to the broadest range of activities that contribute to overall air quality objectives. In contrast to existing emissions trading programs, whose incentives are mostly limited to owners of affected sources, GHG market rules should attempt to extend these incentives to independent investors in worthwhile emissions-reducing activities. In this section we consider some possible methods of achieving this end.

Quantification

Quantification is discussed first because its solutions are potentially simpler to formulate than those for ownership. One obvious way of easing quantification difficulties for investors in projects that displace or reduce demand for emitting generation is to require utilities and/or ISOs *to compile and distribute accurate and detailed emissions rate data*. Such information should be made available continuously, or at least with as much frequency and detail as might be required by quantification rules contained in legislated emissions trading programs.

Even with the availability of this data, however, quantification of emissions reductions would remain a time-consuming and complex deterrent to would-be sellers. Since minimizing the burden of this process would ease investors' ability to generate revenue from the GHG market and make more valuable investments economically viable, governments should consider additional steps to address quantification difficulties. One such step might involve *legal establishment and recognition of a standard "benchmark" emissions rate from existing generation* that could be applied uniformly as a baseline by those claiming emissions reductions. Benchmarks could be established for individual transmission grids to reflect regional differences in generating mixes, and they could differ depending on season, time of day, or other duration as considered appropriate by regulators.

Whatever rate were set, investors in renewables and demand-side management would be absolved of having to calculate and then justify their chosen emissions baselines.

Benchmarks could also be projected into future years on the basis of historical emissions trends. This would allow project developers to "sell forward" emissions reductions that will occur in the future, as a means of financing current projects. The risk for governments of setting standard benchmarks, especially for future emissions rates, is that any degree of abstracting from or averaging actual emissions rates may lead to a discrepancy between the quantity of emissions actually reduced and the quantity of reductions claimed. This risk can be mitigated by statistical analysis to improve the accuracy of benchmarks, and potentially by applying a discount factor to benchmarks that would reflect estimated uncertainty about their accuracy. These measures could help to reduce the burden of quantification for prospective sellers, while preserving the environmental integrity of their claimed reductions and of emissions trading programs in general.

Ownership

Emissions trading market structures fall broadly into two categories, including baseline-and-credit programs and cap-and-trade programs. On the issue of ownership, the key difference the two structures concerns the nature of emissions restrictions imposed on affected sources. This difference requires that unique solutions to the problems of ownership as described above must be made to fit within the context of each distinct market structure.

Rate-Based Emissions Restrictions. In baseline-and-credit programs, emissions restrictions are expressed as a rate of allowable emissions per unit of input such as fuel or production output such as electricity. For example, some sources participating in markets for "discrete emissions reductions" in select US States are allowed to emit a given quantity of NOx or volatile organic compounds (VOCs) per mmBtu of heat input burned for fuel. Sources who operate more efficiently than this allowed baseline rate may earn permits (known as "credits" in a baseline-and-credit context) for the difference between the baseline and their actual emissions. Baseline-and-credit programs are able to accommodate new emissions sources simply by assigning them baselines equivalent or similar to those of existing affected sources.

However, one consequence of these characteristics is that the overall environmental result of baseline-and-credit systems is neither guaranteed nor easily predicted. It is possible that though sources may reduce their rates of

emissions to comply with their baselines, the addition of new sources and growth in aggregate production may result in an overall increase in absolute emissions levels.

On the other hand, it is also these features that make solving problems of ownership a potentially simpler matter in rate-based programs than in capped ones. Governments could create incentives for investors in renewables generators and demand-side management *by assigning standard emissions baselines denominated as allowable emissions per unit of electricity produced or saved*. The particular level of baselines for particular generators or types of activities could be equivalent to, or based on regional "benchmarks" described above. Investors in renewable generation and demand-side management would earn credits equivalent to the quantity of electricity produced or saved multiplied by the baseline allowable emissions rate. Recipients could sell the credits to emissions sources needing to demonstrate compliance, and use the revenue to enhance returns on their existing investments or to re-invest in additional projects. Utilities whose electricity production were affected by displacement or reduced demand would not be able to claim or benefit directly from the same reductions, since their allowable emissions too would be based on production levels. Thus a decline in production would authorize them to emit a smaller aggregate quantity of emissions.

Absolute Emissions Restrictions. In cap-and-trade programs, such as the US SO_2 Allowance Program and the Ozone Transport Commission NOx Budget Program, the regulatory authority begins by establishing an upper limit on overall emissions from a set of affected sources. For example, the SO_2 Allowance Program sets a cap on SO_2emissions from certain electric utilities at approximately 9 million tons per year. Then the regulatory authority creates permits (known in a cap-trade context as "allowances") that authorize emissions equal to the overall cap, distributes these permits amongst affected sources, and allows sources to trade. Cap-and-trade programs are distinct in that their emissions restrictions are expressed as absolute quantities per time, equal to sources' holdings of valid allowances. For example, a source that owns 50,000 valid SO_2 allowances (one allowance authorizes one ton of emissions) at the end of a given year is authorized to have emitted 50,000 tons of SO_2 during that year. It is important to note also that increases in production or new market entrants must be accommodated within these absolute limits either by improving the emissions efficiency of production, or by acquiring surplus allowances from another source. Either way, the number of allowances is finite, and the program's environmental integrity is maintained.

However, this feature complicates the resolution of ownership difficulties for investors in renewables and demand-side management. If governments followed the solution suggested above for rate-based emissions trading programs, a new problem of double-counting would arise, causing inflation of programs' caps. For example, imagine that renewables generators could earn a quantity of allowances proportional to their production of electricity. Existing trading programs contain no provisions for taking back allowances from utilities whose generation declined as a result of reduced production, and creation of such a provision would be extremely unpopular, and of questionable fairness to affected utilities. So if the utilities maintained their full allowance holdings, and new allowances were granted for renewables, the same emissions reductions would twice contribute to sources' compliance—once for the utility whose overall emissions (and emissions liability) were reduced by the displacement, and once for the utility that buys the new allowances from the renewable generators. The resulting increase in the total number of available permits would erode cap-and-trade programs' overall environmental effectiveness. So alternative solutions must be found that create appropriate economic incentives within the confines of absolute emissions caps.

One solution, mentioned above, involves *creation of set-aside bonus pool of allowances for approved activities*. In the SO_2 Allowance Program, 300,000 allowances out of the program's overall cap were set aside in a Conservation and Renewable Energy Reserve. Between 1992 and the turn of the millennium, these were to be allocated to owners of sources that undertook certified investments in renewable energy and energy conservation. Upon conclusion of the program, just over 10% of the bonus pool had been claimed, apparently because the number of allowances that could be earned per unit of energy generated or saved was not high enough to justify many investments. Also, it is important to be clear that allowances in the reserve were only open to owners of sources already affected by the program's mandatory emissions restrictions. Independent investors were not able to claim bonus allowances.

Because bonus pools represent a portion of programs' aggregate caps, they have the advantage of preserving trading programs' environmental effectiveness, and they could also be made open to both affected sources and independent investors. Though double counting might still arise, at least the overall cap would not be inflated. However, since the quantity of allowances placed in the bonus pool is limited by policymakers' initial allocation, the total value that investors could potentially earn from the pool is also limited, though at an unknown quantity which depends on the market price for allowances. This value would be distributed on a first-come-first-served basis, with no opportunity for earning additional allowances except by regulatory decree.

Another means of addressing ownership issues within capped programs concerns programs' basic method of allowance allocation. The SO_2 Allowance Program, whose widely-acknowledged success often makes it a model for design of other programs, allocates allowances to sources according to a formula that assigns a given number of allowances per mmBtu of fuel input, and which is then "ratcheted down," or discounted to ensure that the overall quantity allocated stays within the program's aggregate cap. For example in the program's Phase II that began in 2000, affected sources received an allocation of allowances equivalent to 1.2 pounds of SO_2 emissions per mmBtu of fuel input, discounted to stay within the program's cap of 8.95 million tons of SO_2 per year. Individual sources' average fuel input data from the years 1985 to 1987 is used as the basis for allocations. The program's overall cap is made more stringent over time by reducing the allowable quantity of emissions per fuel input.

Allocating allowances on the basis of output instead of input would level the playing field between affected sources and independent investors in renewables (though not demand-side management, which does not produce per se). Program designers could use a benchmark rate of emissions per unit of electricity produced, discounted to achieve overall target emissions reductions, as a means of allocating allowances. As another variation on the SO_2 Program's allocation methodology, new market entrants could be accommodated by *making the allocation formula dependent on a rolling average of output* such as the three most recent years rather than on a static year or group of years.

Together these solutions would address issues of ownership and, compared to bonus pools, would provide a more flexible incentive structure for renewables investments whose upper limit would be determined only by investors' ability to generate electricity. However, this and the other solutions explored in this section on capped trading programs all essentially consist of a transfer of finite allowances from utilities who possess the allowances now (or would, if existing conventions are followed in future programs) to their competitors. What we have not explored in this discussion are the arguments in favor of the status quo. Issues of fairness to utilities, who already face a difficult challenge to achieve existing emissions reduction targets, and the value of regulatory simplicity, which might be compromised by these solutions, should not be dismissed lightly. In addition, a rolling allocation, in particular, would diminish source's ability to predict their future emissions allocations, and to take cost-effective business decisions in accordance with those plans. A significant loss of regulatory predictability could diminish cost savings and potentially outweigh the benefits of creating new incentives for independent investors.

Conclusion

Expansion of renewable energy generation and demand-side management efforts contribute positively to the achievement of several worthy objectives, such as reducing electricity supply shortages, increasing energy independence, and reducing harmful air emissions. Existing emissions trading programs, despite their indisputable success at reducing the costs of environmental protection, provide unequal incentives for owners of renewables and demand-side management projects. The inadequacy of incentives for independent investors in these activities constitutes a lost opportunity for promoting such activities and correcting market failures that result in under-investment. Though designs of most existing emissions trading programs fail to provide adequate incentives for independent investors, the nascent market for GHG reductions provides perhaps the best context for refining our understanding of these issues. In this context, the two main impediments to creation of incentives for renewables and demand-side management can be thought of as problems of quantification and ownership. While the former issue can be resolved without a great deal of difficulty, solutions to the latter are more elusive. These must be tailored to the structures of the markets in which they would operate, and none is without shortcomings and tradeoffs. Nevertheless, the potential benefits of promoting renewables and demand-side management through emissions market design undoubtedly justify at least a further exploration of these and other possible solutions.

On the Road Again—in the Car of the Future

Josephine Cooper[1]
President and CEO, Alliance of Automobile Manufacturers

It is a pleasure to be here among so many eminent scientists to discuss future energy issues. As a representative of the motor vehicle industry, I speak for makers of products that play a significant role in energy use in the United States. The Alliance of Automobile Manufacturers is a coalition of 13 car and light truck manufacturers, including BMW Group, DaimlerChrysler, Fiat, Ford Motor Company, General Motors, Isuzu, Mazda, Mitsubishi Motors, Nissan, Porsche, Toyota, Volkswagen and Volvo. Alliance member companies have approximately 600,000 employees in the United States (U. S.) with more than 250 facilities in 35 states. Alliance members represent more than 90 percent of U.S. vehicle sales.

Today, I would like to share my vision of the future. But first, let's take a quick peak at the present. Americans still love their vehicles and we are spending more, not less, time in them. Americans purchased a record 17 million vehicles last year. In the U.S., on average, more than 13,000 miles are traveled annually per vehicle. There are more than 205 million vehicles on the road. As an industry, the automakers have made enormous progress in making better and better vehicles with more and more features. At the same time, we've made enormous progress in reducing tailpipe emissions and making vehicles cleaner, supporting standards for cleaner fuels, increasing vehicle safety features, improving fuel efficiency and diversity, and building vehicles with less production waste and higher levels of recycling.

The motor vehicle industry is in a period of change and challenge:

- Global consolidation and alliances among companies continue to occur.
- Companies are fiercely competing for business and on environmental, vehicle safety and energy efficiency advances.

[1]Note that the contents present the views of their authors, not necessarily those of the Department of Energy, RAND, or any other organization with which the authors may be affiliated.

- Technological advances are occurring at a faster pace than ever before.
- Regulatory hurdles are set higher and higher.
- Partnerships with government and allies flourish.
- Consumers are demanding new features and enhanced performance as they choose new vehicles.

The industry is truly at a crossroads as we begin this new millennium. For the last century automakers have been perfecting the internal combustion engine with major advances in electronics, computers and advanced environmental technology. The fuel of choice has been gasoline. Why? Because it simply has provided the most "bang for the buck" in terms of providing performance for cars and light trucks. Moreover, it is widely available, inexpensive, relatively fuel efficient and it is a fuel that consumers have become comfortable with over all these years.

And the gasoline burned in today's cars and light trucks is quickly becoming much cleaner than even 10 years ago. The government regulators, both the California Air Resources Board (CARB) and the Environmental Protection Agency (EPA), have recognized that cars and fuels must be considered as a system, if we are to make our vehicles the cleanest in the world. We, and our partners in the oil industry, can be proud of what we have been able to achieve so far with today's technology –96-99 percent control on smog-forming pollutants. Under the new Federal emission standards adopted for the 2004 model year, and with the continued help of the oil industry, the next generation of vehicles will reduce emissions by another 70 – 80 percent beyond today's already low levels. To give you an example of how far we've come, a personal watercraft (e.g. Jet Ski) pollutes more in seven hours than driving a new car 100,000 miles (that's over four times around the earth at the equator).

Automakers also are working to dramatically improve fuel efficiency. Over the past 20 years, fuel efficiency in all cars has been improved by more than 100 percent. Today's pickup, minivan and SUV get better mileage than a subcompact car from the 1970s. Advanced technologies offer the promise of even greater fuel efficiency gains.

Worldwide, we are working for consistently clean vehicles and fuels. In the World-wide Fuel Charter, automakers around the world have agreed on fuel quality requirements for optimum emissions performance for a range of regulatory regimes. Over the long term, the automakers' goal is to have globally harmonized standards for vehicles and their fuels that represent best practices globally. The fuel charter sets the stage for this to become reality.

What we're here to discuss today at E-Vision 2000 is what will the future look like. The automakers' vision for the future is premised on achieving technological breakthroughs for vehicles. These breakthroughs will embrace additional environmental improvements, enhanced fuel efficiency and vehicle safety. New technologies must be acceptable to the market in all areas, including price, utility, and performance. Clearly, there is a lot on our horizons. Let's take a closer look.

Lean-Burn Gasoline Engine

One promising new technology is the lean-burn gasoline engine, with significant fuel economy advantages over ordinary gasoline engines. These engines need extremely clean gasoline, even cleaner than what was recently adopted by EPA, to allow the use of sophisticated control technology.

Advanced Turbocharged Diesel Engines

An even more promising option is the advanced turbocharged diesel engine for the light duty market. The challenge is to make light duty diesel vehicles as clean and as consumer-friendly as today's gasoline vehicles. This will be a challenge technologically, and it will require much cleaner diesel fuel than in use today. But rising to these challenges will be worth it because diesel technology has the potential for improving fuel efficiency by 40% over today's gasoline engines. In Europe today, clean diesels power more than 25% of the vehicle market. They are quiet, clean diesels (i.e., no black smoke), not the old diesel vehicles that were once sold here in the U.S. or like the "smoky" urban buses we still see in our cities.

Alliance members and other international automakers are working individually and with governments in research and development of advanced technologies. Cooperative research programs between the U.S. industry and government, most notably the Partnership for a New Generation of Vehicles (PNGV), are underway with the goal of achieving technology breakthroughs that will then be integrated into new vehicle fleets. The initiative aims to develop fuel-efficient concept cars having a fuel economy of 80 miles per gallon by 2004 and is investigating fuel cell cars and lean-burn technologies as options with great potential for success.

Hybrid Electric Vehicle

Another emerging technology that is available on the market today is a hybrid-electric vehicle, which combines an electric powertrain with either a gasoline or

diesel internal combustion engine. Electric motors produce a lot of torque -- and for those of you who don't know -- it is torque that is important in quick acceleration, not horsepower. I know because I'm one of those people who like fast, good handling cars. By using the electric motors to provide quick acceleration, the companion gasoline or diesel engine can be made smaller, cleaner and more efficient. Because of this combination of powertrains, hybrid-electric vehicles can provide good performance with excellent fuel economy in city driving, where most of us drive. Toyota introduced the Prius into U.S. markets this year, the first mass-produced hybrid electric vehicle, and other automakers are preparing to introduce more hybrids.

Battery Electric Vehicles

And I can't leave the subject of technology development without mentioning battery-electric vehicles (BEVs). The California Air Resources Board adopted a rule in 1990 that requires automakers to build "zero-emission" vehicles (ZEVs). I won't review the long history of this mandate and all that has transpired, but it is clear from our experience in California that BEVs at best will meet only a niche-market need. While the Alliance member companies have built quiet, comfortable BEVs, in every other way like today's best vehicles, the extremely expensive battery material – which drives the cost of these vehicles very high – and the limited driving range that is available because of the charge capacity of the battery pack, means that this is not a technology we can plan on for the long term.

Alternative Fuel Vehicles

Even with all of these advances, we recognize that society may desire other transportation options. That is why our members have developed alternative-fueled vehicles. Energy sources for these vehicles include methanol, ethanol, compressed natural gas (CNG), liquid petroleum gas (LPG) and hydrogen. Such vehicles have not sold in large numbers – most of these fuels can't compete on a cost and power-per-unit volume with gasoline. Moreover, some of the modifications to the vehicles needed to allow the use of these fuels make these vehicles more expensive. More than 25 variations of alternate fuel vehicles are currently available.

Automakers have learned over the years that consumers like evolutionary change in their vehicles, not revolutionary changes in how things work. Some of the problems of advancing penetration of alternative-fueled vehicles are simply that the fueling infrastructure can be very different from the familiar "pull up to

the pump -- insert nozzle -- and fuel" regime that we are used to today. In addition, in most locations of the U.S., an alternative fuel infrastructure simply does not exist. This is a huge obstacle.

Fuel Cell Vehicles

Beyond these more familiar possibilities, our members also are working to develop vehicles powered by fuel cells. This technology is something the industry is very excited about. Fuel cells combine hydrogen with oxygen to produce electrical energy, offering the promise of zero emissions. The only by product is water vapor. Manufacturers are working hard to make the cost of fuel cell vehicles competitive with today's cars. We aren't there yet, but tremendous strides have taken place.

Now you might remember that fuel cells were used in some of the earliest space flights and, of course, NASA supplied the space capsules with an adequate amount of hydrogen fuel for these devices. We all know that cost and the ability to mass-produce are not the same high priority with NASA as they are in the auto industry.

Fuel cell technology can use any of several sources of hydrogen, including gasoline, methanol and hydrogen gas. The only constant requirement is that the fuel has to be ultra-clean because impurities will prevent the technology from operating. In fact, we may see fuel cells at residential locations for powering homes before we see them commercially for motor vehicles, because it is easier to package the equipment for stationary use and it doesn't require the same sort of infrastructure that vehicles require. This development may hold clues, however, for how the fuel cell vehicle market and infrastructure ultimately develops.

Again, as with alternative-fuel vehicles, the refueling infrastructure will be critically important in determining whether this vehicle technology fills a niche market or plays a more dominant role in the vehicle fleet. Even if gasoline becomes the fuel of choice, it will need to be super clean and may require a separate infrastructure if it is phased in instead of replacing the existing fuel.

One place to watch these developments in vehicle technology and fuel infrastructure is the Fuel Cell Partnership in California. This group includes automakers, energy suppliers, and government agencies, both Federal and State. Their goal is to work on the commercialization of fuel cell vehicles and determine what fuel infrastructure is the most appropriate for these vehicles.

While internal combustion engines will be with us for a long time, we may finally start to see fuel cells replacing internal combustion engines in 10-15 years. As noted above, fuel cells may appear in homes before wide spread use in cars – if there is a reformer in the house to convert some other fuel to hydrogen, it may even be feasible to adapt that system so that the owner can fuel his or her car with hydrogen at home!

Challenges to Advanced Technology Vehicles

There are many "gee whiz" technologies emerging today, but we will not get anywhere without considering consumers. The key to development of advanced technology vehicles lies in overcoming not only the hurdles and obstacles to their commercialization, but also acceptance by consumers. Creating the necessary infrastructure to support advanced technology vehicles is another critical factor in bringing vehicles to market. We need to entice consumers to buy them in sufficient volumes to make them a sustainable part of the market. To do that we must respond to all these consumer priorities: affordability, transparency (and by that I mean that the consumer sees virtually no difference in how she operates and fuels the vehicle), and the same or higher degrees of safety, performance, convenience, environmental controls, utility and reliability.

If successful in meeting emerging regulatory standards plus consumer requirements for price, utility and performance, all of these developments will help stretch our existing petroleum-based energy resources.

Information Technology

Information technology is playing an increasingly significant role in improving overall vehicle efficiency. Automakers are using computers to better manage the energy and environmental systems in their cars and light trucks. Vehicles today have more computer controls than the Apollo rocket that took men to the moon.

One of the most exciting developments on the horizon is the Intelligent Vehicle System, which will feature technology that can help improve both passenger safety and traffic flow. Some of the "intelligent" system features include vision enhancement, lane change and merge assistance, driver electronics, driver monitoring, vehicle diagnostics and rear-end impact warning. There are also automatic cruise controls that respond to the speed of the vehicle in front of you, road departure signals, and intersection stabilizers. Technology enhancements will speed up traffic flow by helping drivers avoid obstacles and minimize driver and vehicle reaction time to road conditions and other vehicles. As traffic flow is

improved, vehicles can operate more efficiently, reducing congestion and pollution, as well as consuming less fuel. What a wealth of choices consumers now have.

Meeting the Future

Whatever happens in the future, it is clear that the auto industry will be a major player, both as producers of the vehicles that consume energy and as the ones who will find solutions to the energy problems in the future.

The industry is making high quality, advanced technology cars today that are ultra-clean, and for their size much more fuel-efficient than cars of the past. This industry is committed to "pushing the envelope" of technology development likely surpassing all of the advances we have made in the past. Given the lead time needed to invent the car or truck or SUV of the future, the developments we see today can only provide clues to a future we really cannot fully comprehend today

Who knows? Maybe someday, we will all dump excess garbage into our vehicle fuel tanks, retract the wheels and contact the nearest air traffic controller as in "Back to the Future." Whatever happens, this industry will be at the forefront of its development. We know many eminent scientists and futurists like you will be part of our vision for the future and we look forward to sharing tomorrow's advancements with you.

Energy R&D Policy in a Changing Global Environment

Charles K. Ebinger[1]
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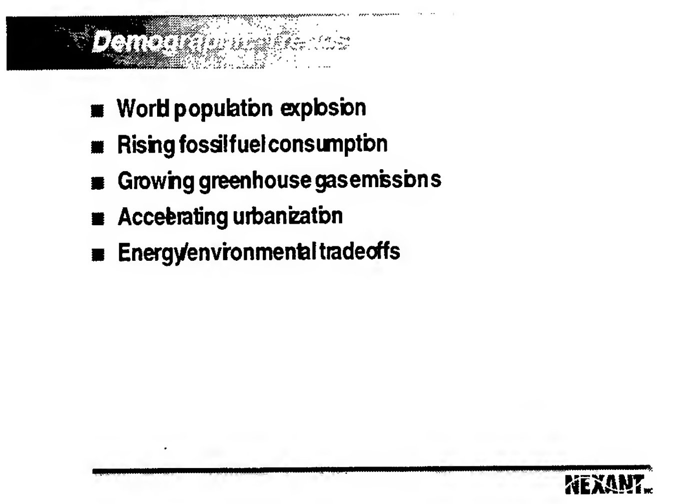
Demographic Trends



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E-Vision 2000

E-Vision 2000

- What is the demographic/institutional context of our energy future ?
- What are the challenges to formulating an effective R&D policy in a changing market environment?

3

Institutional Context

Institutional Context

- By 2020 in the U.S., over 400,000 MW (1,300 plants of 300 MW) of additional capacity will be required to meet electricity demand and replace aging units
- This 400,000 MW includes 73,000 MW of existing fossil (primarily coal -fired) capacity scheduled for retirement by 2020
- Only 49,000 MW of this new capacity is expected to be coal-fired
- Gas turbine combined cycle plants are predicted to grow by 350,000 MW

4

Institutional Context (Cont.)

Institutional Context (Cont.)

- Growing competitive nature of electricity market
- Trading versus owning of electricity
- Transformation of wholesale/retail markets
- Futures contracts
- Internet trading versus owning fuel in market dominated by price/volatility
- Gas versus coal ù changing market perceptions
- Distributed generation (fuel cells, microturbines, diesel, and gas engines)

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5

Institutional Context (Cont.)

Institutional Context (Cont.)

- Uncertain evolution (cost and technical aspects) of the repowering market
- Evolution of non-utility generation market
- Nuclear plant retirements/life extensions
- Renewables ù cascading costs

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6

Institutional Context (Cont.)

Interne

- Emergence of high-powered, low cost platform capable of transforming many utility industry processes
- Early applications have centered on increased trading operations, digitized customer service functions, and aggregation of retail customers in deregulated markets
- Key market growth lies in energy procurement and supply chain management
- What are the benefits of e-procurement? For commercial concerns? For DOE?

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7

International

Internat

- Coal is not dead: it is alive and well!
- India and China will account for 33% of the worldAs primary energy growth by 2020 and 97% of the worldAs increase in coal use
- China will add an estimated 180 GW of generating capacity ù 600 plants of 300MW each
- India will add 50 GW ù 167 plants of 300MW

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8

Summary

Summary

- Coal for electricity consumption will account for almost all the growth in coal consumption worldwide
- Given the large potential export market for clean coal technology and the projected growth in U.S. demand, DOE's R&D budget should take this coal consumption trend into consideration in establishing new R&D priorities

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9

E-Procurement

E-Procurement

- Lower product prices
- Falling procurement costs
- Shorter order and fulfilment cycles
- Reduced inventory costs
- Improved supply change management
- Reduced processing and administrative costs

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10

E-Procurement (Cont.)

E-Proc

Supply Change Management Savings

- TVA
- Bonnevile Power Authority
- Other power authorities
- National laboratories
- Other facilities

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11

R&D

R&D: Where Do We Go From Here?

U.S. DOE

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12

The Future

The Fu

- R&D for R&D's sake will be difficult to justify politically
- Natural gas prices are rising and may change assumptions about the costs of gas-fired generation in absence of additional increases in efficiency

13

The Future (Cont.)

The Future

- Solar industry outlook improving with double digit growth rates albeit from a very low base
- Cost of solar panels is falling owing to declining production costs and enhanced solar panel productivity

15

The Future (Cont.)

- Distibuted geneation: fuel cel costs projected to fal 40-50% by 2005
- HIPPS facilties for repowering and new basebad facilities
- Second-generation greenfield HIPPS facilities using only coal will yield environmental and cost savings

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16

The Future (Cont.)

- Globalwarming ù will second-generation passively safe nuclear reactors get a new look?
- Wil fusion still be 30 years away?

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17

Taking the Time to Ask the Right Questions or, CSTRR: a Case Study with Attitude

Rose McKinney-James[1]
President, Government Affairs, Faiss Foley Merica, Las Vegas, Nevada

During the past year and a half, the nation's attention has been directed toward the growing need to address existing energy policy. Recently, the national political debate has focused on the need to establish a comprehensive energy policy for the country. A substantial amount of attention has been given to the need to balance the interests of the array of stakeholders interested in influencing this policy.

This paper will focus on the need to insure the integration of renewable energy resources as a foundation for national policy. It is based in part upon my experience as a solar advocate in the state of Nevada. It offers one perspective on how energy other advocates might revisit past approaches and seize the ever-elusive "window of opportunity."

The Case for Better Advocacy

Certainly, many would argue that renewable energy resources provide the potential to promote sustainable energy solutions that benefit the environment and improve the quality of life for people around the world.

"Renewable resources," is the common terminology used to describe energy produced by the sun, (solar), the heat of the earth's interior (geothermal), air in natural motion (wind) and biodegradable waste (biomass).

However, if you polled a group of average people with no connection to the renewable energy movement, most would be hard pressed to explain what these terms mean. The complexity of the explanation is a turn-off, even for the intellectually curious. Consumers also seem inextricably tied to old images of

[1]Note that the contents present the views of their authors, not necessarily those of the Department of Energy, RAND, or any other organization with which the authors may be affiliated.

solar and wind energy sources --ugly panels atop roofs and large farms of windmills. The recent improvements in technology, reliability and aesthetics have not replaced the stereotypical images of the seventies. Indeed, many of the most exciting innovations remain trapped in the lab environment.

Key Questions

What's wrong with this picture? How do we translate these complex technological advances into a simple message of opportunity? Why have we not witnessed any significant development of these resources? And why are we not better prepared to pursue energy independence? How can we improve the use of funding resources made available to us by federal and state government to truly promote the broad based use of these resources? How can we effectively secure and leverage private industry participation in this effort? These questions clearly have relevance beyond the borders of Nevada. These are questions that every state must ask itself in light of recent developments. Why do we persist with the "business as usual" mentality? We need answers to these questions and fast.

The CSTRR Experience

Five years ago, the Solar Enterprise Task Force created The Corporation for Solar Technology and Renewable Resources (CSTRR), a not-for-profit tax- exempt corporation. The Task Force was comprised of state, federal, and industry representatives. It was co-chaired by U.S. Senator Richard Bryan and former Assistant Secretary for Energy and Efficiency and Renewable Energy Christine Ervin . CSTRR was created in an effort to address many of the questions raised in this paper.

The following excerpt from the CSTRR Interim Report to DOE is instructive.

> The Mojave Desert may appear to be a desolate wilderness, but this vast dry ecosystem shimmering in the sun's radiant heat is a potential Mother Load of renewable energy.

Nevada is one of the few states in the nation with an exceptional renewable energy resource base. It has been well documented that Nevada has one of the best resources for solar energy in the world. A rich supply of geothermal energy is present in the northern region of the state. Recent studies indicate the presence of a substantial wind resource and the farming, ranching and Lake Tahoe basin represent a tremendous opportunity for biomass production.

After serving as a member of the Nevada Public Service Commission for five years I was recruited to lead the CSTRR effort. As a Commissioner, I frequently questioned the lack of more developed alternative energy resources in the state. I could not understand the logic behind the lack of programs that leveraged the opportunities presented when conservation, energy efficiency and renewable resource deployment were married into a single "zero energy" approach.

This was a common line of questioning used during cross-examination of Commission witnesses. I suppose when you raise such questions in a public forum it becomes more likely that you find yourself called upon to 'walk the talk.'

I left a comfortable and visible position as the Director of the Nevada Department of Business and Industry (B and I) to become the CEO of a solar advocacy organization. B and I is a monster agency. It regulates everything from banks to dairy farms, insurance, mining and industrial relations. It was a fast-paced, invigorating and productive ride. However, my tenure with CSTRR became the most stimulating and incredibly challenging, interesting and informative journey of my career to date.

CSTRR made historic strides that are just being recognized today. Over a short period of five years the Corporation made sizable inroads to be sure, but fell considerably short of expectations. Some would argue that these expectations were unrealistic. Others cite timing, Nevada's low energy rates, and an unprecedented robust economy as the culprits. In 1995 Nevada utilities posted some of the lowest rates in the west. In addition, most energy related decisions were made in the shadow of pending retail competition and utility deregulation. I believe these issues factored significantly into CSTRR's ability to convince consumers and policy makers that renewable energy technologies deserved the funding necessary to explore innovative ideas for technology deployment.

Identification of Critical Barriers

The most significant achievement for CSTRR came with the tremendous support of the Department of Energy through FEMP, NREL and the Western Area Power Administration. These organizations recognized the value of innovation and agreed to collaborate with CSTRR in an effort to identify federal facilitates interested in the purchase, installation and demonstration of solar technology.

As a result, CSTRR secured over 80 megawatts in commitments from federal agencies for the purchase of solar energy. The process that followed included a

targeted message to a customer representing the largest consumer of any goods and products in the world, the United States government.

Using the federal government as the primary focal point, we embarked upon an aggressive campaign to create a leadership model for the use of renewable resources in the US. This experience also allowed us to identify a number of significant barriers. These barriers became the foundation for detailed review and action.

Without exception, the most significant barriers identified as a result of the CSTRR experience related to cost, pricing, and the general economic factors and affordability of the solar systems.

If we truly want to establish reasonable/effective strategies to limit the use of fossil fuels in the future, we must be realistic in the approaches we adopt today. We need a well-informed consumer willing to demand the supply of these technologies.

It's the Market

In market development the practice of preaching to the choir is a recognized point of failure. I am far more interested in the challenge of creating a compelling argument to convince the opposition than gaining the cheers of fellow advocates. I do not believe that those who disagree with my position on the issues are automatically unenlightened or enemies. *Over zealous, inaccurate advocacy is tantamount to silence* and is definitely counterproductive. Failure to target a message with the appropriate audience dooms any effort. Conflicting messages and messengers make for a mess. Allowing old techniques to rule the day creates dinosaurs. The use of silly acronyms and abbreviations simply is not cool. It takes too long to decipher. In these days of e-commerce when transactions can be completed in seconds, time becomes a critical issue. Time is money. Such is the lament of decision-makers who wish to be helpful but are lost in the morass of the all too often technical explanation.

For the purpose of this panel discussion, I maintain that the key to sustaining the market for renewable energy systems will be the success of the marketing efforts and public relations campaigns in delivering the key messages identified in product specific research. Putting the safety and health of the environment uppermost in the mind of the consumer will be necessary in order to sustain awareness of the product and its intrinsic benefits. Programs, which are focused on customer choice, should be leveraged in marketing materials and advertising. But we need solid input from the consumer, the general public and the end user.

It is imperative that professional media coverage, both broadcast and print. *System installations must pass the tests of reliability, aesthetics, and performance.* These efforts should focus upon the environmental benefits and the general economic benefits being offered to the individual consumer and the community and large must be emphasized. Research undertaken today must focus on improving performance and reducing costs. The results of this research should be available to the public. This type of credible and meaningful advertising for systems will invariably help sustain sales of the products.

It is also imperative that a strong and well targeted initial marketing effort be developed. This requires industry to conduct quantitative and qualitative research on the target market segments identified in each market to assist in the creation of successful marketing tools.

Every state should have a well-identified central repository for renewable energy data. As such, organizations like the Interstate Renewable Energy Council should play a more central role in seeking input to develop stakeholder based recommendations to help establish priorities for policy/decision makers.

Customer Choice

Friday nights at my house have become a ritual. My week, like most professionals', is full of meetings, transportation nightmares and various levels of preparation for future activity. Friday is the day to refocus and begin a wind-down process. With a four-year- old, life rarely provides the opportunity for an occasional chardonnay, instead it means pizza!

As I understand it, most people enjoy really good pizza, ergo its popularity. One of the reasons is that pizza allows for such a variety of combinations -- from the divinely simple to the outrageously sinful. With this in mind, my family makes several selections to meet the range of tastes. The meal is easy and over quickly. *The key issues here are ease of process, familiarity, efficiency, satisfaction, and creativity. But most of all, in a word: CHOICE.*

There are many approaches that may be undertaken to broaden the acceptance of renewable energy technologies. There is no single approach. Instead, we must take advantage of the data, which has been collected over the past decade. It clearly indicates that customers prefer choice. Depending upon demographics, price drives this choice.

Economics drive customers. Customers drive markets. But first, they must be informed, educated and challenged.

Last year, Susan Dibella authored a provocative article for *UNLV Magazine*. In the article entitled "The Value of Research," she explores the extent to which the average person appreciates research.

> To most of us, the term "research" conjures visions of white-coated scientists mixing potions in test tubes or bespectacled scholars poring over dusty volumes in a library basement. But how does research really happen and why is it so important?

In the article, research efforts are described as essential, misunderstood, and too complex to provide a direct relationship with a result. I can relate. During my tenure with CSTRR a significant amount of my time was devoted to public interaction. It is difficult to translate the degree of frustration that stems from attempts to explain the value of "renewable energy resources." While many enlightened consumers understand and appreciate the concept most haven't a clue. If I stop to say solar or wind, the reaction is different. The most embarrassing question researchers face relates to explaining why the resource was not more readily available. A typical reaction may be, "Call me when I can I pick this up at Home Depot or Lowes." Or, "Does this stuff come with the purchase of my new home?" A Nevada favorite, " I love solar, the fuel is free so sign me up!"

An Effective Message

A few months ago the Merica Agency, the Nevada-based advertising and consulting firm associated with my firm, Faiss Foley Merica, developed a research process for its clients dedicated to building the brand/message and providing a strategic direction to implement the results. The MPACT Process was designed to assist our clients in developing and maintaining their brand. It helps the client with market positioning and consumer testing. It insures that all marketing efforts from public relations to database marketing to Internet marketing to consumer and trade advertising remain strategically on target. This is just one of many approaches that the renewable energy community might adopt to improve its ability to move technologies from the research phase to market based product.

Conclusion

The vast majority of scientists in the world believe that there is value in taking affirmative steps to conserve energy, reduce emissions and redirect industrial environmental practices. Research suggests that these steps will lead to a

substantial reduction in the potential for global warming. The need to explain the importance of this position has been made clear.

Developing economies are desperate for power to run hospitals, schools and to put their human and natural resources to work.

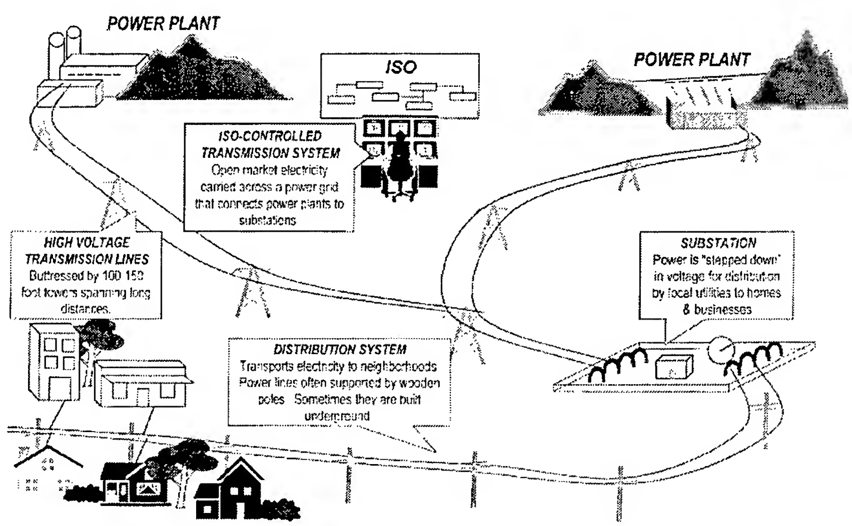
As the national debates rage, it is critical that advocates take advantage of the focus to craft an effective message. This cannot occur until the experiences of researchers and image-makers merge to craft the right message. Whether we chose to promote distributed generation or chose another approach we must seek the right input to answer the right questions. But first, we must ask the right questions.

Distributed Generation Architecture and Control

Robert C. Sonderegger[1]
Director of Modeling and Simulation, Silicon Energy Corporation, Alameda, California

The traditional roles of utilities as energy suppliers, and consumers as energy users, are morphing rapidly. The confluence of deregulation with advances in telecommunications and information technology has opened new opportunities to decentralize generation.

For example, power generation is no longer limited to centralized power plants. The technology is available to generate power at all levels, whether at the transmission, distribution, or at the end user levels. As the interconnections



SOURCE: Cal-ISO website.

Figure 1—Deregulated Power Production, Transmission, and Distribution

[1]Note that the contents present the views of their authors, not necessarily those of the Department of Energy, RAND, or any other organization with which the authors may be affiliated.

become more complex, and many actors produce and consume power simultaneously, traditional SCADA (Supervisory Control And Data Acquisition) is inadequate to handle, let alone optimize, all possible combinations of power production and consumption.

Below we will review some of the control issues arising from this brave new world of distributed power generation and some of the technologies that make its control possible.

Distributed Generation Controlled Using the Internet

With progressing utility deregulation we are witnessing a transformation in energy production, where small engines, microturbines, fuel cells, and renewable systems are deployed locally to generate power close to where it is used. Hospitals and grocery stores have maintained backup power generators for a long time. Co-generation has been used as an on-site source of power for decades. Heat recovered from co-generators is harnessed to offset on-site heating loads and thus adds to the economic benefits.

But only the recent utility restructuring and market deregulation has brought local power generation into the realm of economic competitiveness. New schemes are being tried to resell power from traditional backup generators to secondary markets. Power and heat from co-generation is made available to facilities organized into a Power Park. These schemes mark the trend from traditional, Central Generation to new, Distributed Generation.

Distributed Generation (DG) is defined as the integrated or stand-alone use of small, modular electric generation close to the point of consumption. Power sources that fit the definition of DG, also termed *GenSets*, are:

- Internal combustion engines coupled with generators;
- Gas turbines powering generators;
- Microturbines (small, cheaper gas turbine packaged with a generator);
- Fuel Cells;
- Renewable Systems (PV, wind turbines);
- Loads that can be curtailed on demand (interruptible lighting circuits, chillers, etc.).

As the number and diversity of DG on the grid increases, dispatching these resources at the right time and accounting for the flow of energy correctly become complex problems that require reliable monitoring and tele-metering equipment, as well as an independent entity to settle billing for power trades. Another challenge is to ensure reliable communication and control between distributed resources and loads. Traditional SCADA (Supervisory Control And Data Acquisition) systems with centralized control rooms, dedicated communication lines, and specialized operators, are not cost effective to handle a large number of DG resources spread over the grid.

New communication technology and software has become available to transform traditional SCADA systems in a way reminiscent of Personal Computers transforming Mainframes. The Internet provides a convenient point-to-point communication network that replaces dedicated telephone lines. Inexpensive computers equipped with suitable communication and control software manage the distributed resources. The necessary control software is installed on a single server. Its functions are:

- monitor the operational health of a large number of GenSets;
- issue alarms and shut down GenSets if alarms go unheeded by human operators;
- automatically schedule and dispatch GenSets in an economically optimal manner;
- accept manual input from human operators.

A human DG operator need not be in physical proximity to the server with the control and monitoring software. All she requires is a PC with Internet access. Using a regular browser she can review the status of all GenSets, resolve alarm conditions, and issue manual dispatch commands to selected GenSets if needed. This can be done from an office, a home, or an airport lounge, as shown in the figure below.

While managing servers connected to GenSets over the Internet may appear to be the modern solution of choice to control Distributed Generation, it is not without problems:

- Despite its overall reliability, the Internet is a public communication network subject to local congestion or ISP server outages that can temporarily interrupt the connection between Controllers and GenSets– therefore, any control strategy must be designed with fail-safety in mind such that the

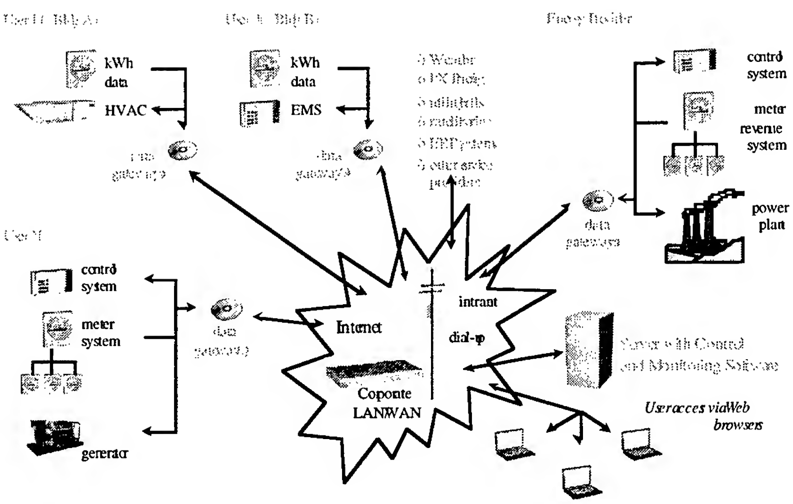


Figure 2—Monitoring and Control of Loads and Distributed Generation at Many Buildings Using the Internet

GenSet at the end of the line "knows how to do no harm" while temporarily off-line;

- There are currently many communication protocols by which GenSets report their operating conditions and accept control commands—a Controller must be able to speak many GenSet control languages in order to be effective;
- To perform a complete optimization, in real time, of the economically optimal dispatch level of each GenSet on a grid can be a daunting.

Economic Dispatch as a Means to Control DG

In what follows we will variously refer to GenSets and to Controllers. GenSets are power-producing devices. Controllers are software suitable to monitor, dispatch, and optimize the operation of GenSets. When optimizing the operation of many distributed GenSets on a grid, it is useful to distinguish between several hierarchical levels of control, each described in the following sections.

Device Level Control

This level is at the GenSet itself. In order to be usable as DG resources operated remotely, GenSets must possess a local, on-board firmware controller with some built-in intelligence. The logic in this on-board controller gives the GenSet the

ability to run in an "Autopilot" mode for periods of time when no communication exists with a remote software controller. Note the use of the word "controller" both for local, on-board logic at the device level (on-board controller), as well as for control software running on a remote server (software controller).

A typical Autopilot mode for an on-board controller is Threshold Load Control, whereby the GenSet adjusts the power supplied to the connected load such that the residual power requirement from the utility grid never rises above a constant level, called the Threshold. This Threshold level is periodically adjusted upward or downward by the software controller in response to a drop or a rise in utility grid power price, respectively.

On-board controllers also monitor the health of the GenSet, such as:

- exhaust temperatures and rotation speed in turbines and internal combustion engines;
- operating temperature in fuel cells;
- output power, voltage, and frequency, for all GenSets.

If any monitored quantities exceed pre-programmed limits, an alarm message is issued and sent to the software controller, as soon as in communication with the onboard controller. If the software controller fails to respond, or if human intervention is required but none is forthcoming after a set period of time, the on-board controller can shut down the GenSet.

Thus the on-board controller fills operational safety and dispatch requirements in the case of temporary loss of communication with the software controller.

Site Level Control

A Site is defined as one or more facilities connected to one master meter. Examples of sites are:

- Single buildings;
- Clusters of buildings, or Campuses with multiple buildings all belonging to the same organization;
- PowerParks with multiple facilities that buy their power in common, as depicted below.

At the Site level a number of DG resources must satisfy the power needs of many diverse loads. Physical proximity may enable the utilization of heat recovered

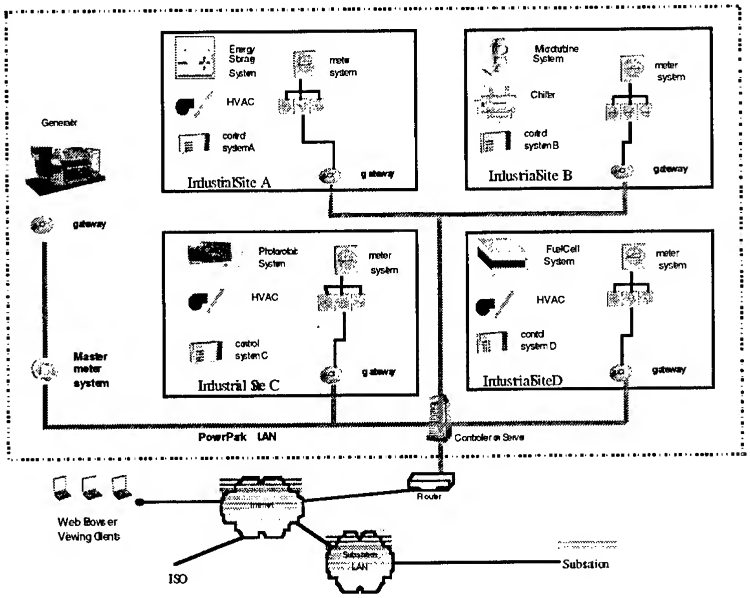


Figure 3—PowerPark Consisting of Multiple Facilities Sharing Grid and DG Power Supply

from DG to offset thermal loads within the site. It may be useful to picture the interplay of DG and loads within a site as a network.

In the figure, natural gas flows both to drive DG and to satisfy building loads. Electricity is produced by DG and consumed by building loads. Heat recovered from DG is used to offset thermal loads in buildings and thus decreases the gas or electricity requirements at the building level.

Emissions are also produced by both DG and by building equipment. Generally speaking, additional emissions are offset by reduced emissions at the building and at the remote power plant used to produce power for the buildings.

accomplished by minimizing overall energy costs in real time. Schematically the overall energy cost at a Site with N GenSets and M facilities can be computed as:

$$\$Total = \$GenSetTot_1 + \$GenSetTot_2 + \ldots + \$GenSetTot_N$$

$$+ \$FacilityTot_1 + \$FacilityTot_2 + \ldots + \$FacilityTot_M$$

At the site level, economically optimal dispatch of the DG resources is Each GenSet cost in this equation results from adding the cost of fuel consumption, of capital depreciation, and of O&M costs:

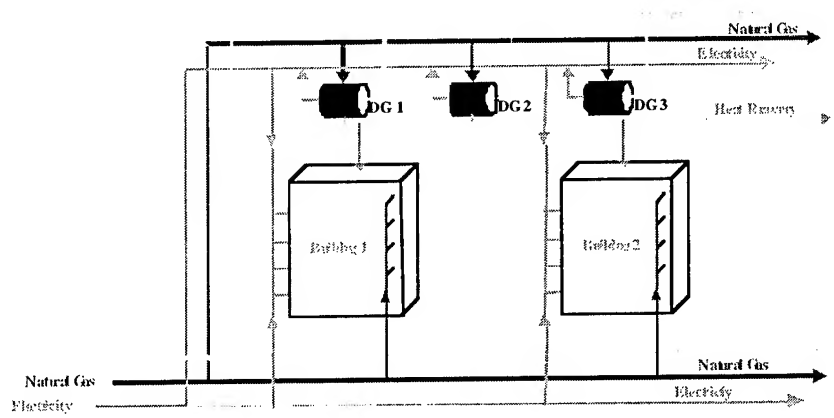


Figure 4—Schematic Representation of Site-Level DG: Building loads draw power from grid or from DG. Natural gas is used to drive DG or building loads. Heat recovery from DG offsets thermal loads.

$$\$GenSetTot_1 = \$GenSetFuel_1 + \$GenSetCap_1 + \$GenSetO\&M_1$$

Each facility cost in this equation is the result from adding electricity and natural gas:

$$\$FacilityTot_1 + \$FacilityElec_1 + \$FacilityGas_1.$$

If there were only one GenSet and only one facility at the site, and the one GenSet were dispatched by itself, the cost of running the facility would decrease while the cost of running the GenSet would increase. On which side the balance of costs tips is a function of:

- the relative prices of electricity, of natural gas, and of the GenSet fuel;
- the GenSet electrical and thermal efficiencies;
- the degree to which the heat recovered from the GenSet can be utilized to offset thermal loads in the facility.

Cheap fuel costs, high electrical and thermal efficiencies, and high degree of heat recovery, all favor operating the GenSet.

The same optimization can be effected when many facilities on a common master meter are connected to a network of many GenSets. The cost equation to be minimized may have more terms, but the principle is the same: operate the GenSets whenever the incremental cost of DG-produced electricity, taking into account capital depreciation and O&M, equals or exceeds the savings in utility-

supplied power and natural gas to the facility. The savings are the result of the following mechanisms:

- locally produced DG power displaces utility-supplied power, kWh for kWh;
- heat recovered from DG offsets thermal building loads and thus reduces electricity and/or gas use.

Retail gas and electric tariffs are often known many months ahead. Even in a fully deregulated market, they are known at least one day ahead, typically in the form of 24 hourly prices. Facility loads are a function of operating conditions and weather. Fairly reliable day-ahead load forecasts can be made at a facility level for at one day ahead.

Thus, within the accuracy limit of the weather and operating condition forecasts, the dispatch of a GenSet can be planned at least one day ahead, in the form of up to 24 different part-load levels. This requires that the Threshold Load control for the GenSet be reset to a new threshold up to 24 times a day. In many practical cases (e.g., a TOU tariff), one or two threshold level resets per day will suffice.

Control at the Utility Level

There are distribution utilities that own a fleet of GenSets and want to dispatch them economically, as shown in the figure below.

Dispatch decisions will be made by comparing the additional cost of running DG assets, with the savings from purchasing less peak power from producers. Market prices paid for primary power vary by season, time of day, and with the degree of congestion on transmission line paths required to deliver the power. In an economic sense, local DG affords the utility some hedging capabilities.

But DG dispatch decisions at the utility level are rarely made with economics alone in mind. Other factors, such as power quality at the microgrid and ancillary services required by the ISO, play a role at least as important. For a utility the timely response to alarms and the scheduled dispatch of DG resources are often deemed too important to be left to an automatic dispatch controller, as can be done on a Site level.

Mixed Site-Level and Utility-Level Control

An interesting hybrid of control is provided by the following arrangement: GenSets are distributed over many sites in one distribution utility service territory where they are automatically scheduled day-ahead by site-specific controllers

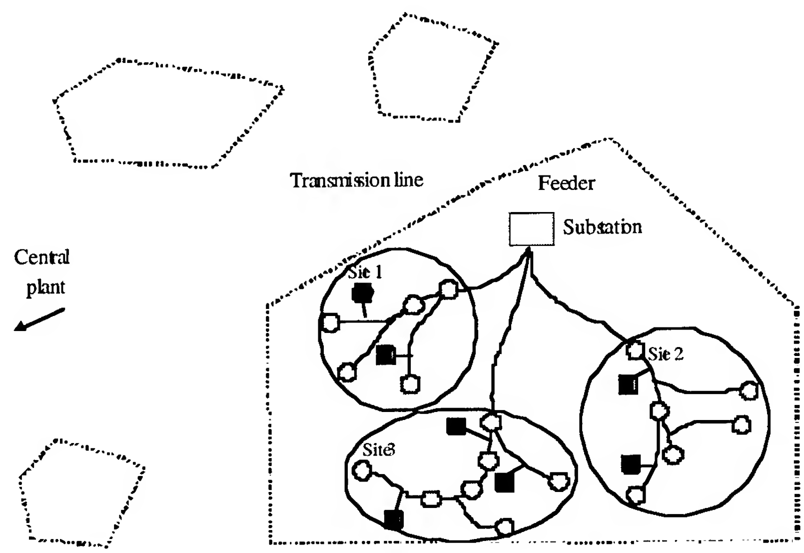


Figure 5—Utility Service Territory Composed of Multiple Microgrids (polygons). Each microgrid consists of many sites (ovals), each containing DG (cylinders) and facilities (opaque circles). Utility can override site-level DG optimization by direct dispatch of selected GenSets over the Internet

As the distribution utility requires additional, unscheduled power in specific parts of its service territory, it can call upon selected resources not currently dispatched to meet local loads. Economic tradeoffs between additional electric consumption at the site level and reduced power purchased by the utility can be made to decide on which resources to "hijack" in this way.

Distributed Energy Network

To obtain the full benefit of local generation, we may have to change our thinking from the existing order of a software controller dispatching DG, to a *Distributed Energy Network* of loads and GenSets. In a Distributed Energy Network power can be generated and consumed at every node of the network, and many resources can meet the loads on the network. In this context an energy resource is any device which can produce energy, shift load through storage, or curtail the demand for energy.

In a Distributed Energy Network there is no central controller optimizing dispatch schedules of all GenSets. Instead, each GenSet and each Load is

represented by an intelligent software agent that "knows" the current state and forecast state of its owner. This information is regularly published through a standardized software interface. For example, a GenSet agent broadcasts its day-ahead capacity availability and bid price through a standardized software interface. A Load agent, meanwhile, broadcasts its day-ahead load forecast. Transmission agents broadcast the day-ahead tariff for carrying power over particular trunks of the grid. An automated software auctioneer patterned after what is used in online auctions today matches bids to requests and sets the market-clearing price.

Barriers to Distributed Generation

Considerable technological and regulatory hurdles lie in the way of the brave new world of Distributed Generation and Distributed Energy Networks. Current transmission grid and switching hardware is ill suited to "running in reverse," that is, to allow DG power to flow from end use points back into the grid. The complexity of grid interconnection increases in the order listed below, from easiest to most complex:

- Run DG in isolation—no grid interconnection;
- Run DG in isolation but allow load to switch from DG to grid and back;
- Connect DG to grid without power export to the grid;
- Connect DG to grid with export (bi-directional power flow).

Current buyback tariff structures (Net Metering and Flat Rates) provide little economic incentive to DG owners to sell back excess power to the utility.

Among the recommendation to advance DG are:

- to promote market mechanisms by which power produced locally by DG is fairly paid for at a price that reflects its actual value to the utility, for example in terms of avoided transmission costs;
- to promote uniform requirements under which DG is permitted to supply power to the grid;
- to extend existing ISO and PX entities to promote an active market of DG buyers and producers within utility service territories and across different utilities.

A. Scenario Analysis

Richard Silberglitt
RAND

Anders Hove
RAND

RAND undertook an analysis of future scenarios to help inform EERE's planning process. Scenarios are used as descriptions of alternative futures, not as forecasts or predictions. They enable policymakers to systematically consider uncertainties inherent in energy planning and to select strategies that are robust. Robust strategies perform adequately over a range of conditions, in contrast to those that do very well under some conditions, but fail under others.

This appendix describes the methodology and results of the scenario analysis undertaken as part of the E-Vision 2000 process. This analysis indicates the range of representative scenarios that are documented and familiar to energy experts, aggregates these scenarios into a smaller set that can be clearly distinguished from one another, and illustrates some of the policy actions and strategies implied by these scenarios. It is important to note that this analysis did not extend into a full-fledged strategic planning process.

In the planning phase of the E-Vision 2000 process, the scenario analysis was anticipated to provide conference participants with a common basis for discussion of widely available energy scenarios. In practice, the insights from the scenario analysis were not integrated into the panel discussions of the Policy Forum. By design, they were not used by participants in the Delphi process either.

The analysis did highlight essential similarities and differences among the many energy scenarios that have been published in recent years, and served to illustrate how such scenarios and studies can provide policy insights despite the uncertainty associated with long-term projections. Additional work is needed to take these scenarios to the point where the implications for energy R&D can be more clearly focused and useful to EERE.

An analysis of future scenarios was undertaken to inform EERE's strategic planning. Clearly, major uncertainties will influence the future evolution of U.S.

energy supply and use. For example, future U.S. energy consumption and fuel mix will likely depend upon:

- Energy intensity of the economy (quadrillion BTU/$ GDP);
- Absolute value and amount of variation in oil prices, the possibility of oil price shocks, and the stability (security) of oil supply;
- Availability of increased amounts of natural gas in North America, to meet increased demand without the need for increased intercontinental (LNG) transport;
- Extent to which the current carbon-intensive fuel mix is accepted, or efforts to "decarbonize" are intensified;
- Rate of adoption of renewable technologies in all end use sectors;
- Fraction of electricity derived from nuclear power (i.e., rate of decommissioning of existing nuclear plants and whether new plants will be built).

To address these uncertainties, scenarios are used as descriptions of alternative futures, not as forecasts or predictions. By regarding a range of possible futures, not just the most likely future, we can cope with the uncertainty that is inherent in energy planning, and select strategies that are robust (perform adequately in all future situations), rather than fragile.

To do this, possible futures must be described in sufficient detail and within a common framework so it is possible to distinguish them on important parameters and ensure we are truly regarding a set that is broad enough to span the scenario space. We do this by defining the scenarios associated with these futures with a common set of metrics or parameters.

This allows us to develop *signposts* to alert us to the approach of undesirable futures or gauge our progress toward desirable futures.

It also allows us to compare the paths associated with alternative futures with history to develop some sense of how "heroic" paths to desirable futures are. We can then develop *hedging strategies* to help ensure we can cope with undesirable futures (or take advantage of desirable ones), and *shaping strategies* to help ensure we can achieve desirable futures. These elements, signposts, hedging strategies, and shaping strategies are the building blocks of an adaptive approach to strategic planning that can help the U.S. avoid undesirable outcomes and move toward desired futures despite the uncertainty inherent in energy planning.

Method of Scenario Analysis

RAND's scenario analysis team defined a set of parameters that could provide a common framework to compare and contrast the large number of commonly used energy planning scenarios in ways that were meaningful for policy development. This framework was then used to identify groupings of individual scenarios that comprised "meta-scenarios," representing a plausible set of alternative futures that met two criteria:

- They must be sufficiently parsimonious to be used for policy planing in a practical sense, and
- They must cover a sufficiently broad range of possible futures to provide a robust basis for informing policy decisions.

These meta-scenarios were then assessed to determine the signposts, hedging strategies, and shaping strategies needed for an adaptive approach to strategic energy planning.

Scenario Parameters to Define a Common Framework for Analysis

A sufficient set of metrics, or parameters, is required to provide a common framework to compare and contrast scenarios. Without clearly defined parameters that can capture important distinguishing features of scenarios (e.g. economic growth and environmental and socio-political impact as well as energy use), we run the risk of incorrectly assessing importantly different scenarios. For example, a scenario with current energy use in 2020, together with substantial economic growth (enabled by increased energy productivity), and a scenario with current energy use in 2020, together with economic stagnation, represent very different futures. A sufficient set of scenario parameters will describe the significant social, political, and economic aspects of the envisioned future, as well as the details of energy supply, demand, and use. Thus, we define three categories of parameters: *sociopolitical parameters*, *economic parameters*, and *energy parameters*.[1]

[1] We use constant 1996 dollars for the economic measures in this report.

Sociopolitical Parameters

From a sociopolitical viewpoint, energy is not an end, but rather a means or a tool to achieving desired outcomes, e.g., food, shelter, comfort, transportation, products, trade. The types and quantities of energy needed and used depend both on the structure and behavior of society and on the existing energy supply and end-use infrastructure. If these are well-matched, then the energy sector functions smoothly. However, if required quantities of fuel are unavailable when needed, or end-use patterns change rapidly, or in unanticipated ways, or infrastructure breaks down, disruption occurs. Such disruption can have economic impact (e.g., lost production), can cause personal inconvenience (e.g., power outages, gas lines), and can affect political decisions (e.g., trading partners, military alliances). An estimate of the possible level of disruption is an important sociopolitical metric that is difficult to quantify. Accordingly, we will recognize the differences between scenarios by providing a qualitative estimate of the potential for disruption as high, medium, or low.

That a scenario has low potential for disruption merely specifies that energy demand patterns, infrastructure, and supply are well-matched. It does not mean that the scenario has no sociopolitical impacts. For example, high energy prices can have significant and regressive societal impact. The use of energy causes a variety of environmental and health impacts. Regulations that limit these impacts have costs as well.

The following are the sociopolitical parameters used as scenario descriptors in this study.

SP_1: Potential for Disruption (high, medium, or low)

SP_2: Energy Contribution to the Consumer Price Index (percent)

SP_3: Cost of Health and Environmental Impacts and Regulatory Compliance ($/MBTU)

Most scenarios do not provide information on parameters SP_2 and SP_3.

Economic Parameters

The following parameters are used to describe the economic aspects of the scenarios. Monetary measures are in constant 1996 dollars.

EC_1: GDP Growth (percent per year)

EC_2: Inflation Rate (percent per year)

EC_3: Energy Price Inflation/Overall Price Inflation (ratio)

EC_4: Fuel Taxes, Energy Subsidies, and R&D Expenditures ($/MBTU)

Most scenarios provide information on GDP growth, but few provide information on inflation. Many scenarios do not provide full information on taxes, subsidies, and R&D expenditures. In some cases, policy surrogates are used that allow estimation of these parameters.

Energy Parameters

The following are the energy parameters used in this study. They characterize energy supply and demand, as well as the fuel mix and end use system.

EN_1: Total Energy Consumption (Quadrillion BTUs per year)

EN_2: Decarbonization[2] (dimensionless, with unity corresponding to exclusive coal use, and infinity corresponding to exclusive use of non-fossil fuels)

EN_3: Energy Productivity of the economy ($ GDP/MBTU)[3]

We call scenarios "full" energy scenarios when they provide data on all of these energy parameters. Scenarios that provide data on some, but not all, of the parameters, or provide incomplete data, are called "partial" scenarios. In addition to full and partial scenarios, we also analyzed some technology studies that provide useful input data for energy scenarios. We note that parameters EN_2 and EN_3 provide alternative means to reduce environmental impacts of energy use, the former through fuel mix changes and the latter through improved supply or use technologies or behavioral change. We also note that metric EN_3 is not independent of parameters EC_1 and EN_1. It is nonetheless important in its own right as a measure of the amount of energy needed to sustain a unit of GDP.

[2] This is measured by the weighted sum of energy consumption per fuel type, normalized to total energy consumption, where the weights reflect the CO_2 emissions of each fuel per MBTU of energy consumed.

[3] We refer to this ratio as *energy productivity* to emphasize the fact that it includes more than the simple efficiency of electrical devices. Importantly it also includes the effects of sophisticated production and use choices that are increasingly available to us because of information technology – such as avoiding the production of excess inventory and using automated timers to control heating and air conditioning in buildings.

Analysis of Selected Individual Scnearios

Scenarios Investigated

Quantitative scenarios, i.e., those containing a complete quantitative description of energy consumption and fuel mix versus time (which we term "full" scenarios) were obtained and reviewed by RAND from a wide range of different sources, as summarized in Table 1.

- EIA Scenarios based upon econometric and technological (sectoral consumption) models (EIA Annual Energy Outlook 2000)
- Scenarios based upon EIA's analysis of compliance with the Kyoto Protocol on CO_2 emissions reduction
- Econometric scenarios: IEA, GRI, AGA, IPAA, DRI, WEFA
- World energy scenarios (WEC/IIASA)
- Sustained growth and dematerialization (Royal Dutch Shell)
- Intergovernmental Panel on Climate Change (IPCC)
- America's Energy Choices (ACEEE, ASE, NRDC, UCS, Tellus Institute)
- Bending the Curve Scenarios (SEI/GSG)
- Inter-laboratory Working Group: Scenarios of U.S. Carbon Reductions

The EIA Reference Case, with its 5 variants, and its 32 Side Cases (20 of which were fully quantified), as described in *Annual Energy Outlook 2000*, provided a baseline. These scenarios are extrapolations of current trends and policies, using a combination of econometric and technological (sectoral consumption) models.

The EIA report, *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity* (October 1998), includes 6 scenario variants that use the DOE economic and technological models, with an added carbon price component included in the price of each fuel, plus 5 sensitivity cases that vary economic growth, rate of technological improvement, and nuclear power use. EIA followed this report with *Analysis of the Impacts of an Early Start for Compliance with the Kyoto Protocol* (July 1999), which revisited the same assumptions together with implementation beginning in 2000. The carbon prices were reduced somewhat but the conclusions were unchanged.

Scenarios based upon econometric models developed by multi-national and non-governmental organizations were included in the study, e.g., International Energy Agency (IEA), Gas Research Institute (GRI), American Gas Association

(AGA), Independent Petroleum Association of America (IPAA), Standard and Poors DRI Division, Wharton Econometric Forecasting Association (WEFA).

The World Energy Council (WEC), together with the International Institute for Applied Systems Analysis (IIASA), in the report, *Global Energy Perspectives (Cambridge University Press* (1998), describe 6 world energy scenario variants that span a broad range of alternative futures.

Royal Dutch Shell Energy Group describes one scenario variant in which growth in energy consumption is sustained at a high rate, and one scenario variant in which "dematerialization" slows energy consumption.

The Intergovernmental Panel on Climate Change (IPCC) describes 6 scenario variants with different assumptions about economic, population, and technological growth.

The American Council for an Energy Efficient Economy (ACEEE), Alliance to Save Energy, National Resource's Defense Council, and the Union of Concerned Scientists, in consultation with the Tellus Institute, describe 3 scenario variants based upon high energy efficiency and investment in renewable energy, together with substantial changes in the energy infrastructure.

In the report, *Conventional Worlds: Technical Description of Bending the Curve Scenarios*, the Stockholm Environment Institute and Global Scenario Group describe 2 scenario variants driven by intervention to reduce carbon emissions and transition to renewable energy sources.

The Inter-Laboratory Working Group of five DOE national laboratories, in the report, *Scenarios of U.S. Carbon Reduction: Potential Impacts of Energy-Efficient and Low-Carbon Technologies by 2010 and Beyond* (1997), describes 2 scenario variants in which public policy actions and market intervention lead to reduced carbon emissions.

The Interlab Working Group's 2000 report, Scenarios for a Clean Energy Future, describes three additional scenarios involving policy interventions such as increased Federal R&D and domestic carbon trading programs.

A number of scenarios that did not provide a fully quantitative picture of the energy consumption and fuel mix were also reviewed. We termed these "partial" scenarios.

The President's Council of Advisors on Science and Technology (PCAST), in the report, *Powerful Partnerships: The Federal Role in International Cooperation on Energy Innovation* (June 1999), makes quantitative estimates of reductions in fossil fuel

use, U.S. oil imports, and CO_2 and other emissions possible with increased investment in energy RD&D.

Professor Jesse Ausubel of Rockefeller University, in the paper, *Where is Energy Going?* (The Industrial Physicist, February 2000), describes the decarbonization of the fuel mix in "pulses" of rising energy consumption per capita, with natural gas as the 21st century transition fuel to hydrogen.

Joseph Romm, Arthur Rosenfeld and Susan Herrman, in *The Internet and Global Warming*, argue that e-commerce spurred recent improvements in U.S. energy efficiency, and posit future increases in efficiency beyond extrapolation of current trends, with concomitant reductions in energy consumption.

Amory Lovins and Brett Williams, in *A Strategy for the Hydrogen Transition*, envision stationary fuel cells powering buildings and providing distributed generation of electricity, resulting in the reduction of size and cost of fuel cells and hydrogen infrastructure, and ultimately cost-effective fuel-cell-powered ultra-high efficiency "hypercars."

Several technology-specific scenarios were also reviewed.

The California Air Resources Board (CARB) study, *Status and Prospects of Fuel Cells as Automobile Engines*, examined the cost of hydrogen infrastructure for automotive fuel cells, as well as methanol and gasoline as hydrogen sources.

Arthur D. Little, in the report, *Distributed Generation: Understanding the Economics*, provides a detailed market study of fuel cells, co-generation, small gas turbines, and microturbines for distributed electricity generation.

The U.S. Energy Information Administration, in chapter 3 (Future Supply Potential of Natural Gas Hydrates) of *Natural Gas 1998: Issues and Trends*, describes the vast reserves of methane trapped in hydrated form in deep undersea and Arctic deposits, and discusses the technological prospects for recovery.

The study, *Solar Energy: From Perennial Promise to Competitive Alternative*, performed by the Dutch Firm KPMG and sponsored by Greenpeace, proposes construction of large-scale (500 MW) photovoltaic power plants as a way of decreasing the cost of solar electricity.

The National Renewable Energy Laboratory published several reports detailing the current state of federal renewables research. *Photovoltaics: Energy for the New Millenium*, projects growth rates of photovoltaic systems and reductions in system costs, including an industry-developed roadmap with photovoltaics

providing 10% of electricity by 2030. The Federal Wind Energy Program envisions prices of wind energy to fall to 2-4 cents by 2002. Further research and development could lower this price to 1-3 cents by 2015.

The DOE *Biomass Power Program: Strategic Plan 1996-2015* aims at establishing partnerships between the DOE and the private sector to revitalize rural economies through the introduction of biomass fuels. This report describes the potential of biomass power to grow to 30,000 megawatts of capacity, employing 150,000 in predominantly rural areas, and producing 150-200 billion kilowatt-hours of electricity by 2020. Finally, the *Strategic Plan for the Geothermal Energy Program* envisions that by 2010, geothermal energy will be the preferred alternative energy source around the globe. By 2010, this program intends to supply electricity to 7 million U.S. homes (18 million people), and meet the essential energy needs of 100 million people in developing countries by installing U.S. technology for at least 10,000 megawatts of power.

Analysis of Each Scenario

This section details the RAND analysis of each of the planning scenarios assessed in this report.

EIA forecasts:

Reference, high/low GDP, and high/low oil price cases

Inputs (assumptions)
No policy change
GDP, oil prices remain key drivers of energy consumption, fuel mix
Efficiencies increase gradually
No *lasting* economic, geopolitical, or oil price shocks

Method
Integrated econometric and technological models
Detailed projections of fuel consumption by sectors, appliances, vehicles, etc.

Outputs (Energy Consumption & Fuel Mix)
Continued reliance on fossil fuels, dramatically higher oil imports, natural gas and coal consumption
Nuclear cut in half in line with projected plant decommissioning
Renewables, fuel cells insignificant to 2020

Issues and Implications
High reliance on oil imports, vulnerability to economic, price shocks
CO_2 emissions unabated

SOURCE: RAND analysis.

Figure A.1— EIA Reference Cases

EIA Reference Cases. The EIA Reference Case assumptions for GDP and oil prices and its variants represent a relatively narrow range of extrapolations based upon the recent past. Real GDP grows at 2.2 percent annually for the Reference Case (1.7 and 2.6 percent in the low and high GDP variants). Reference Case oil price is $22/barrel in 1998 dollars ($15 to $28 per barrel in the low and high oil price variants). EIA acknowledges that its oil price forecasts show "far less volatility than has occurred historically." (Oil price has ranged from $12.00/barrel to $57.00/barrel in 1996 dollars.) It is questionable if these 5 cases reflect a wide enough range for effective policy analysis.

In the EIA Reference Case, growth rates in energy demand in residential and commercial sectors drop due to lower population and building additions. Additionally, industrial sector growth drops due to lower GDP growth and increasing focus on growth in less energy-intensive products. Similarly, transportation sector growth declines somewhat due to slower growth in light-duty vehicle travel. In each sector, a variety of complex technological and policy assumptions are made, most of which hinge on maintaining existing policy levels as a minimum, with additional technological improvements possible.

EIA projects large growth in natural gas consumption, although its forecasts are somewhat lower than, for example, those of the American Gas Association (AGA) and the Gas Research Institute (GRI). The EIA report acknowledges high uncertainties associated with the environmental acceptability of coal boilers and the adoption of natural gas technology. The source of natural gas is clearly an important policy issue.

In the EIA Reference Case, U.S. energy consumption in 2020 is 121 quadrillion BTUs. The high/low GDP and high/low oil price variants suggest this level could be as high as 130 or as low as 112 quadrillion BTUs.

The industrial and transportation sectors continue to dominate growth in energy consumption, accounting for approximately 75 percent of the growth projected to 2020. Although the residential and commercial sectors are projected to continue growing, their energy consumption gradually levels off toward 2020 in all five of the main EIA variants. The Side Cases discussed later, which assume increased adoption of new technologies, lower the sectoral consumption curves somewhat, although these variants show a larger effect in the two smaller sectors (residential and commercial) than in the industrial and transportation sectors.

In all five Reference Case variants, the fuel mix remains largely unchanged, with fossil fuels accounting for a larger fraction of energy supply than in 1997. Energy derived from natural gas rises almost 40% (an increase of 9 quads), while oil rises 36% (an increase of 13 quads) and coal rises 29% (an increase of 6 quads). Nuclear energy falls by almost 40% because of the assumption of decommissioning of nuclear plants on schedule. Renewable energy from all sources continues to account for between 7 and 8 quadrillion BTUs. The continuation of the existing fuel mix, together with increased energy consumption, raises policy issues associated with both supply (oil and gas) and use (coal). The low rate of adoption of renewables and the decommissioning of nuclear plants eliminate from the fuel mix potential low CO_2 options.

In the EIA Reference Case, domestic oil supply continues to drop steadily, while oil imports rise over 50%. Even the EIA high oil price variant shows steady and large increases in oil consumption, with imports continuing to supply a larger share. This suggests the need for energy policy to deal with security of supply or hedge strategies for replacement fuels.

Note that the rise in natural gas described in the previous slide will require substantial increases in domestic production or a similar level of increased gas imports. Domestic production of natural gas peaked in the early 1970s at about 22 trillion cubic feet (Tcf), declined until 1987, then increased to reach its current level of about 19 Tcf a few years ago. Natural gas well productivity peaked in

1971 at 435 thousand cubic feet per day per well, then declined to its current level of about 180 thousand cubic feet per well per day by 1985. Substantial price and policy incentives may be required to achieve the projected increased domestic production of 27 Tcf per year. Moreover, the source of this increased domestic production is assumed to be from growth in the current proven reserves of approximately 164 Tcf.

Any shortfall in domestic production, resulting from either lack of available reserves or too slow a rate of extraction, will necessitate increased natural gas imports. Will these gas imports be obtained via pipeline from Canada (currently the source of more than 90 percent of U.S. natural gas imports) or Mexico, or via LNG shipments from South America, the Middle East, or Asia? With respect to the North American sources, the relevant question is magnitude and rate of additions to reserves. For the other sources, it is the required cost and infrastructure investment, and the safety ramifications.

EIA Side Cases:
Four key groups

- **Slow change (9 variants):**
  - **2000 technology variants**
  - **low oil and gas technology variant**
  - **electricity high nuclear variant**
  - **electricity low fossil and low demand variants**
- **Faster adoption of advanced technology (12 variants)**
  - **10 high technology variants**
  - **2 high building efficiency variants**
- **More change, same consumption (10 variants)**
  - **remaining electricity, oil, gas, and coal variants**
- **Electricity high demand variant (1 variant)**

SOURCE: RAND analysis.

Figure A.2— EIA Side Cases

EIA Side Cases. The 32 EIA Side Cases fall into four key groups. The first group comprises variants resulting in slow change relative to the Reference Case. The "2000 technology" variants all suppose that technology available in 2000 will be used but no new technologies will be adopted. The "low oil and gas technology" and "electricity low fossil and low demand" variants also assume no or slow technology improvement, while the electricity high nuclear also results in only minor change. (In the high nuclear case, plants are decommissioned at a slower rate.)

The advanced technology variants make more aggressive assumptions about the adoption of new technology. Several "best-available-technology" cases assume rapid building-shell efficiency growth as well as immediate adoption of best available technology. Four "high technology" sector variants assume earlier availability, lower costs, and higher efficiencies for advanced equipment. Finally, two building sector variants assume 25% and 50% increases in building efficiency to 2020.

The remaining electricity, oil, gas, and coal variants examine the effects of various policies such as electricity competition, mine-mouth prices, and renewables pricing subsidies, all of which lead to energy consumption similar to

that of the Reference Case. Finally, the electricity high demand variant (upper center) assumes demand growth of 2%, as opposed to 1.4% in the Reference Case, resulting in substantially higher energy consumption. This variant requires even more natural gas than the reference case, focusing even more sharply the issue of natural gas supply.

EIA Special Cases

Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity (October 1998) and Analysis of the Impacts of an Early Start for Compliance with the Kyoto Protocol (July 1999)

Inputs (Assumptions)

The cost of compliance with the CO_2 emissions targets of the Kyoto Protocol will require incorporation of carbon cost in energy prices

Method

Inclusion of a carbon cost in fuel prices, based upon the carbon content of fuels at the point of consumption

Use of DOE model to determine the carbon cost to achieve specific levels of CO_2 emissions

Outputs (Energy Consumption & Fuel Mix)

Dramatic reduction of coal use and substantial increases in natural gas, renewables and nuclear energy, with respect to the DOE Reference Case.

Issues and Implications

Political and economic impact of higher energy prices

Requirements for technology and infrastructure development for fuel mix changes

Level of electricity consumption and amount from nuclear

SOURCE: RAND analysis.

Figure A.3— EIA Special Cases

EIA Special Cases. In the EIA report, Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity (October 1998), six different carbon reduction cases, characterized by total U.S. CO_2 emissions in 2020, are compared with the 1998 EIA Reference Case. These cases are: the 1990 level (1340 million metric tons, hereafter referred to as "1990") + 24%; 1990 + 14%; 1990 + 9%; 1990; 1990 – 3%; 1990 – 7%. (The Reference Case corresponds to 1990 + 33%.) For each case, the reduction in CO_2 emissions is achieved by applying a carbon price to each of the energy fuels relative to its carbon content at its point of consumption. The EIA model is then used to calculate the carbon price necessary to achieve the stated level of CO_2 emissions. These carbon prices range (in 2010) from $67 per metric ton (1996 dollars) in the 1990 + 24% case to $348 per metric ton in the 1990 – 7% case.

In the October 1998 report, it was assumed that the carbon prices were implemented in 2005. The July 1999 report examined the impact of implementation in 2000. This reduced carbon prices in 2010 from $60 per metric ton (1990 + 24% case) to $310 per metric ton (1990 - 7% case). While the detailed impact on the economy is somewhat different, the energy policy implications remain unchanged.

The total energy consumption and fuel mix for each carbon reduction case are determined from the EIA technological and economic models, with the additional carbon price component included in the price of each fuel. Because of the increase in energy prices, 2020 total energy consumption is always lower than the EIA Reference Case, ranging from 98.8 quads (1990 – 7%) to 108.6 quads (1990 + 24%). All cases show a dramatic reduction in coal use, as compared to a slight increase in the EIA Reference Case, with the 1990, 1990 – 3%, and 1990 – 7% cases reduced to about 3 quads, compared to the current level of 22 quads.

Oil consumption in 2020 is higher than the current level, but less than that of the EIA Reference Case, while natural gas consumption is higher than that of the EIA Reference Case. The contributions of renewable and nuclear energy to the fuel mix in 2020 are significantly higher than the EIA Reference Case, reflecting faster technological development and adoption for renewables and extension of the life of existing nuclear power plants. In the 1990 – 7% case, 13 quads of renewable energy and almost 8 quads of nuclear are used in 2020, as compared to 7 quads and 4 quads, respectively in the DOE Reference Case.

In addition to the 6 carbon reduction cases, EIA analyzed 5 sensitivity cases, as follows: high and low economic growth (2 cases); faster and slower availability and rates of improvement in technology (2 cases); and construction of new nuclear power plants (1 case). Each sensitivity case was constrained to the same level of carbon emissions as the case to which it was compared, so that the principal difference was in the carbon cost required to achieve the stated level of emissions. The high technology and low economic growth cases lead to lower carbon prices, with concomitant higher energy consumption, while the low technology and high economic growth cases lead to higher carbon prices, with lower energy consumption. The overall fuel mix observations described in the previous paragraph are still valid.

The nuclear sensitivity case introduces the possibility of growth in nuclear power by allowing the construction of new nuclear power plants, and also by relaxing assumptions in the reference case of higher costs associated with the first few advanced nuclear plants. Under these assumptions, in the 1990 – 3% case, it was found that 41 gigawatts, representing about 68 new plants of 600 megawatts each, were added. The total energy consumption in this case is about 1.8 quads higher than the 1990 – 3% case, or 101.7 quads, still about 15% less than the EIA Reference Case. Carbon price is $199 per metric ton, as compared to $240 per metric ton for the 1990 – 3% case. Because of the lower energy prices, energy consumption is higher, but the presence of increased nuclear power allows the carbon emissions target to be met with a higher level of energy consumption.

These reports explicitly identify the costs associated with reducing CO_2 emissions, and tracks the fuel mix changes that are necessary within a plausible set of scenario variants to achieve those reductions. Price increases are projected for all fuels, with the greatest impact on coal and natural gas. (Despite the higher carbon content of oil, the impact of carbon price on natural gas is greater because of differences in tax and pricing structures for these fuels, especially the high taxes on oil.) The increases required in natural gas, renewables, and nuclear power, relative to the EIA Reference Case, underscore further the policy issues raised in earlier slides with respect to oil imports, sources of natural gas, development and adoption of renewable technologies, and decommissioning of nuclear power plants. The nuclear sensitivity case provides one explicit example of an alternative electricity scenario that can be used as a basis for policy analysis.

Other Econometric Scenarios:
IEA, GRI, AGA, IPAA, DRI, WEFA

Inputs (Assumptions)

- Economic growth, oil prices remain key drivers of world energy picture
- Few dramatic efficiency gains or new fuel alternatives—no substantial change in energy picture to 2020
- No sustained economic or geopolitical disruptions

Method

- Integrated economic models assuming conservative economic growth and oil price changes

Outputs (Energy Consumption & Fuel Mix)

- Substantially similar to present fuel mix
- GRI suggests much higher natural gas usage, lower gas prices, extensive distributed generation

Issues and Implications

- High reliance on oil imports, vulnerability to economic, price shocks
- CO_2 emissions unabated
- "Portfolio" of energy sources less diverse

SOURCE: RAND analysis.

Figure A.4— Econometric Scenarios

Econometric Scenarios. Other econometric scenarios share many of the characteristics of the EIA projections, and their results are also similar. The most dramatic differences appear in the fuel mix. The Gas Research Institute (GRI) projects a dramatic drop in U.S. coal supply as environmental impacts of coal boilers become unacceptable, whereas Standard and Poors' data research division (DRI) and Wharton Econometric Forecasting Associates (WEFA) both suggest much higher domestic coal consumption, with still higher coal exports. (EIA projects that coal exports would fall off due to declining OECD reliance on coal for electricity generation.) The GRI and the American Gas Association (AGA) scenarios both include dramatic increases in natural gas consumption in residential, commercial, and industrial sectors, whereas gas consumption in residential and commercial sectors is assumed to level off by DRI and WEFA. All of these scenarios call for increased natural gas consumption, although in the WEFA and DRI scenarios these gains come about primarily as a result of industrial sector fuel mix changes.

Like the EIA Reference Case, the econometric scenarios tend to rely on assumptions about economic growth and oil price stability that resemble the experiences of the past decade. Oil prices fall in the $15-$25/barrel range for

most of the econometric scenarios, with the exception of IEA, which considers a range from $20/barrel to $30/barrel between 2010 and 2015.

In the transportation sector, the econometric scenarios are broadly similar in their assumptions; most project slower growth in number of vehicles driven than in the past few years. The GRI scenarios are more aggressive, suggesting relatively rapid gains in vehicle efficiency.

World Energy Council (WEC) / International Institute for Applied Systems Analysis (IIASA)

Inputs (Assumptions)

- 1992 World Bank population estimates
- By 2100, all countries and regions successfully industrialize and accelerate economic growth
- Patterns of energy usage converge
- Existing high-efficiency technologies become economical
- Fossil fuels sufficient for 100 years

Method

- Economic model; incorporates technological, environmental, agricultural changes

Outputs 2100 (Energy Consumption & Fuel Mix)

- All cases characterized by reduction of dependence on fossil fuel, increased reliance on electricity, and increased use of renewables.
- Cases differ by magnitude of energy use.

Issues and Implications

- Resource availability not a major global constraint?
- Technological change will be critical for future energy systems
- Decarbonization will improve the environment at local, regional, and global levels

SOURCE: RAND analysis.

Figure A.5— WEC and IIAS

WEC and IIASA. The World Energy Council and the International Institute for Applied Systems Analysis analyzed six possible futures that fall within three broad categories. Each scenario spans the globe until 2100 and demonstrates the dependence of energy futures on geopolitics, policy intervention, and the world economy.

Case A assumes a world of free trade and favorable geopolitics; by 2050 there is a five-fold increase in World GDP, and by 2100 a fifteen-fold increase. This increase in wealth leads to an increase in consumption; between 2030 and 2100, U.S. and Canadian total energy use increases to over 160 Quads/year. Electricity dominates the scene, responsible for 3/4 of all fossil energy consumed.

Case B takes a more cautious approach to geopolitical and international trends while allowing for a conservative increase in economic expansion. Between the U.S. and Canada, total energy usage peaks in 2030 at 120 Quads before leveling off. Here too, electricity is dominant.

Case C is characterized by strong policy elements that determine the distribution and use of particular fuels. Scenarios phasing out nuclear power entirely as well as developing small-scale, safe, and publicly accepted nuclear plants are

investigated. Between the U.S. and Canada, total energy usage drops to just over 35 Quads/year by 2100. While use of alternative fuels such as hydrogen and solar power increase, less energy is used overall. Both energy consumption and economic growth in the case C variants are substantially lower than in cases A and B.

Royal Dutch Shell:
Sustained Growth and Dematerialization

Inputs (Assumptions)
Follows World Bank population estimates
Two scenarios: "Sustained Growth" continues the 20th century's pattern of energy per capita increases, providing energy at competitive prices on the open market
"Dematerialization" posits advances in materials and design capabilities increasing efficiency and demanding a lesser energy input

Method
Model developed by Shell analysts; details not provided

Outputs (Energy Consumption & Fuel Mix)
Sustained Growth: world consumption 140 million Btu/capita by 2060 (c.f. 73 million Btu/capita today). Fossil increases until a plateau 2020–2030, when renewables increase
Dematerialization: world consumption reaches 84 million Btu/capita by 2060. Increase in gas; delayed introduction of photovoltaics

Issues and Implications
Need for hydrocarbons
Alternative fuel use selected by market forces

SOURCE: RAND analysis.

Figure A.6— Royal Dutch Shell

Royal Dutch Shell. Recognized since the 1970s as a pioneer of scenario analysis, Royal Dutch Shell continues to make available to the public some details of its world energy scenarios. Two of these scenarios displayed on Shell's web site are "sustained growth," and "dematerialization."

Shell's "sustained growth" scenario is essentially a business-as-usual scenario for the world economy, positing little fuel mix change by 2020, followed by increases in the share of renewable energy, although fossil fuels continue to grow in absolute terms.

Shell's "dematerialization" scenario, on the other hand, posits rapid change in consumer lifestyles, as well as increased technological growth enabling miniaturization of many resource-intensive activities. In some respects, dematerialization is a more radical version of the changes brought about recently by the Internet, a technology that has enabled some substitution of virtual activity for physical services and products. In dematerialization, however, economic activity is curtailed to some extent following 2020. Technological change takes place mainly in the area of dramatically increased efficiency, leading to reduced demand. In this scenario, the consequent drop in the absolute world demand for energy ultimately stifles development of clean energy technologies.

Intergovernmental Panel on Climate Change (IPCC)

Inputs (Assumptions)

Assumptions about economic, population, and technological growth

A1 – economic convergence, good world economy, gains in efficiency, clean fuel

A2 – "regionalism," high population growth, lower economic activity and trade

B1 – economic convergence, absolute focus on environment over economy

B2 – "regionalism," with emphasis on local environment, not global climate

Method

World econometric model driven by social factors leading to differing levels of regional economic growth, trade, and population

Outputs (Energy Consumption & Fuel Mix)

Dramatic changes in fuel mix, energy efficiency—depending on cultural and societal commitment to reduced emissions, acceptance of international cooperation on environmental and economic matters

Issues and Implications

Cultural change is a central driver of world environmental policy

Attitudes toward economic and political regionalism can result in differing commitment to emissions reduction

SOURCE: RAND analysis.

Figure A.7— IPCC

IPCC. The Intergovernmental Panel on Climate Change (IPCC) has developed a number of scenarios to examine the effect of world social developments on global emissions of CO_2. These scenarios vary mainly by their assumptions of regional levels of economic growth, population growth, and trade. The scenarios also include descriptions of cultural factors driving macroeconomic change, such as regionalism, traditionalism, or global cultural convergence.

IPCC describes its four scenarios in the following general terms: Scenario A1 is a rapid economic growth, low population growth model involving rapid technological change and profound increases in efficiency and clean fuel adoption worldwide. Regions converge culturally and economically. Scenario A2 involves high population growth, lower economic growth, and "strengthening regional cultural identities" centering around traditional values and lifestyles. Scenario B1, like A1, involves rapid advancement of clean fuels, and energy efficient technologies, with the emphasis on environmental improvement rather than on economic growth. Finally, Scenario B2 envisions a world driven by regionalism regarding cultural, environmental, and economic systems. In B2, technological change and clean fuels play a smaller role than in A1 and B1.

The IPCC reports are unique in acknowledging the central role of cultural and political trends in driving policy regarding energy efficiency and clean energy.

ACEEE, ASE, NRDC, UCS, Tellus Institute:

America's Energy Choices

Inputs (Assumptions)

Reference based on DOE case

Three alternative scenarios reflect the same level and quality of energy services, but with a lesser cost and smaller environmental impact—a result of higher energy efficiency, efficient power supplies, infrastructure changes, and renewable energy investments

Method

Adopt least expensive efficiency and renewable resources, proceeding to more expensive ones as needed; economic and technological factors incorporated

Outputs (Energy Consumption & Fuel Mix)

Alternative scenarios project primary energy needs from 82–62 Quads in 2030, compared to the reference of 120 Quads the same year.

Reference projects a 15% increase in oil consumption; alternative scenarios project a 40–54% decrease. Renewables constitute 36–53% of fuel mix by 2030.

Issues and Implications

Strong policy elements required at all levels of government

SOURCE: RAND analysis.

Figure A.8— ACEEE, A8E, NRDC, UCS, Tellus Institute

ACEEE, A8E, NRDC, UCS, Tellus Institute. America's Energy Choices is a series of energy scenarios published by the American Council for an Energy-Efficient Economy, the Alliance to Save Energy, the Natural Resources Defense Council, and the Union of Concerned Scientists, in consultation with the Tellus Institute. These scenarios are based on economic assumptions found in the DOE Reference Case; however, additional scenarios variants are developed in which individuals and companies pursue a higher rate of investment in cleaner fuels and greater energy efficiency than would occur under DOE assumptions.

In the most aggressive scenario, "climate stabilization," energy consumption is cut in half versus the DOE Reference Case in 2030, with half this energy derived from renewable sources. The report also states that the improvements in energy efficiency and clean fuel adoption would result in $5 trillion in consumer savings, with only a $2.7 trillion increase in additional investment required to bring about these changes.

Less aggressive are the "market" and "environmental" scenarios. The "market" scenario focuses on increased substitution of renewable energy "at market penetration rates," without additional policy changes to support efficiency or clean fuel technology. The "environmental" scenario assumes more rapid

penetration rates, as well as some increased policy focus on efficiency and clean fuels. All three scenarios, according to the report, result in trillions of dollars in net cost savings over the DOE Reference Case. Notably, most of the efficiency gains portrayed in these scenarios comes about in the residential, commercial, and transportation sectors, with less relative change in industrial energy demand. The report describes a broad range of policies but does not explicitly relate specific policy actions to specific scenario characteristics.

Stockholm Environment Institute
Global Scenario Group:
Conventional Worlds, from *Bending the Curve*

Inputs (Assumptions)

- Both developing and developed world undertake dramatic energy policy intervention to combat CO_2
- Developing world poses largest potential CO_2 problem

Method

- Forecasts driven by targets (efficiency and renewable use), with macro-economic and energy use trends adjusted to meet those targets

Outputs (Energy Consumption & Fuel Mix)

- Eventual transition to all renewable energy, particularly biomass and wind in the near term, followed by solar and hydrogen fuel cells in the far future

Issues and Implications

- High political and economic costs to adoption of aggressive policies
- Possibility technologies will not turn out as hoped, or that existing technologies or fuels will remain competitive, keeping renewables out at the margin

SOURCE: RAND analysis.

Figure A.9— Stockholm Environment Institute

Stockholm Environment Institute. "Bending the Curve Scenarios," from the Stockholm Environment Institute Global Scenario Group, examines the changes necessary to reduce and nearly eliminate CO_2 emissions worldwide by 2075, with much of the out-year emissions coming from developing countries. The report shows that a variety of changes would be needed to meet such a target, from dramatically increased public transportation, efficiency mandates, convergence between developing and developed worlds in energy-use patterns, and an assumed dramatic increase in biomass, solar, wind, solid waste, geothermal, wave, and tidal power. Non-hydropower sources of electricity grow to 35% of world electricity generation by 2050 in the most aggressive scenario, compared with 16% in the study's reference scenario.

Inter–Laboratory Working Group

Scenarios of U.S. Carbon Reductions and
Scenarios for a Clean Energy Future

Inputs (Assumptions)

- Modified EIA reference case from Annual Energy Outlook (AEO) 1997
- Existing information on performance and costs of technologies to increase energy efficiency and decarbonization
- Projections of certain specific technological improvements

Method

- Each report creates three quantitative (implying six total) models: one "efficiency" case, utilizing public and private–sector efforts, and two scenarios with carbon permits
- Earlier report taken to 2010, later report to 2020

Outputs (Energy Consumption & Fuel Mix)

- Compared with EIA, the first ORNL report As "efficiency" scenario reduces energy growth from 22 quads to 15 quads, and high–efficiency/low–carbon case reduces further to only a 9 quad increase; the second ORNL report shows energy grow6h to 2010 of between 5 and 12 quads
- $50/ton permit case reduces carbon emissions in 2010 to 1990 levels (achieved by 2010 in earlier report, by 2020 in later report)

Issues and Implications

- Combined efforts of government policy, industry incentives, and private investments required to achieve these results

SOURCE: RAND analysis.

Figure A10— Inter-Laboratory Working Group

Inter-Laboratory Working Group. In two reports -- Scenarios of U.S. Carbon Reductions (1997) and Scenarios for a Clean Energy Future (2000) -- the Inter-Laboratory Working Group proposes scenarios that address the role of energy-efficient technologies and carbon trading in reducing U.S. carbon emissions. Two strategies are considered: (1) an "efficiency" case in which both the public and private sectors engage in an accelerated R&D program and active market alteration activities, and (2) two variants on a "high-efficiency/low-carbon" case in which federal policies and tradable emissions permits (at either $25 or $50 per ton of carbon) are used to respond to an international emissions treaty.

These reports consciously avoid predicting what policies will have what effect, simply assuming that policy intervention of some form could achieve these effects. Potential sources of improvements come from renewables research (biomass, wind, renewables in buildings) and several opportunities for breakthroughs in technology (building technology advances, light-duty vehicle advances).

The 1997 report's efficiency case suggests an approximate cost of 25-50 billion 1995$ and energy savings of 40-50 billion 1995$ by 2010, with carbon savings of

100-125 MtC. The 1997 report's high-efficiency/low carbon case suggests costs of 50-90 billion 1995$, projected savings of 70-90 billion 1995$, and carbon savings of 310-390 MtC.

The 2000 report's projections extend to 2020. In its moderate scenario, the report suggests energy savings of 10 quadrillion Btus and carbon emissions reductions of 86 MtC. In its advanced scenario, energy savings are 22 quadrillion Btus, and carbon emissions reductions are 382 MtC.

President's Commission of Advisors on Science and Technology (PCAST):
Powerful Partnerships

Inputs (Assumptions)
Business-as-Usual energy consumption entails substantial economic, environmental and societal costs and risks
Increased energy RD&D can provide technological advances to help mitigate these costs and risks

Method
Bottom-up technological and sectoral analysis to evaluate potential reductions in, e.g., energy demand, oil imports, and CO_2 emissions

Outputs (Energy Consumption & Fuel Mix)
Reduced coal, reduced oil imports, increased natural gas, biomass, renewables, and nuclear fission (as compared to all DOE variants)

Issues and Implications
Large funding increases proposed, but a small fraction of U.S. energy expenditures. Potential returns include lower energy costs, less imported oil, cleaner air, and increased flexibility for achieving CO_2 reduction

SOURCE: RAND analysis.

Figure A.11— PCAST

PCAST. The EIA Reference Scenario and other Business-As-Usual forecasts assume continued reliance on fossil fuels, including increased U.S. oil imports and continued use of coal, leading to growth in energy consumption and CO_2 emissions in the developing world that exceed current world totals.

The President's Commission of Advisors on Science and Technology (PCAST), a broadly-based group of distinguished academic and industrial experts, argues that the costs and risks inherent in this situation justify increased investment in energy RD&D that will allow the development and implementation of advanced energy supply and use technologies that can more rapidly reduce reliance on fossil fuels, U.S. oil imports, and CO_2 and other emissions. This includes: 25% more energy-efficient buildings, 50% efficient microturbines, 100 mpg passenger cars, doubling-tripling of truck fuel efficiency, advanced fuel cells, CO_2 sequestration, extended operation of existing nuclear reactors and development of new reactors with improved safety and mitigated fuel cycle risks and impacts, increased cost-effective wind, photovoltaic, solar thermal and biopower systems, and a more rapid transition to biofuels and hydrogen. PCAST estimates that U.S. oil imports could be reduced to about 15 quads in 2030, approximately the 1990 level, with continuing reduction in later years.

The proposed increase of one billion dollars in 2003, compared with the 1997 level of energy RD&D funding, represents less than a fifth of a percent of the combined 1996 energy expenditures of U.S. firms and consumers, and as such, could yield a very high return on investment.

Romm, Rosenfeld, and Herrman:

The Internet and Global Warming

Inputs (Assumptions)

- Technological change fastest in Internet sector
- Adoption of the Internet, and use for conducting business, results in lifestyle changes with impacts on overall energy picture

Method

- Description of recent energy consumption, GDP trends employing macroeconomic data

Outputs (Energy Consumption & Fuel Mix)

- Lower consumption, increased efficiency, with reduction in lifestyle
- Little change in fuel mix – lower transportation may reduce oil consumption

Issues and Implications

- Technological solutions need not rely on new fuel sources – efficiency remains an option, albeit under uncertainties
- Efficient technologies (e-commerce) may not even be energy-related

SOURCE: RAND analysis.

Figure A.12— Romm, Rosenfeld, and Herrman

Romm, Rosenfeld, and Herrman. In "The Internet and Global Warming," by Joseph Romm, Arthur Rosenfeld, and Susan Herrman, the authors note that in 1997 and 1998 U.S. energy intensity (energy per dollar GDP) improved by 3%, compared with 1% in previous years. The authors believe that this improvement can be attributed to the rise of the Internet, with attendant increases in telecommuting, reduced retail and office space, and fewer trips for errands. Although the authors note that data on these changes are still preliminary, they also note that the potential changes in commuting, shopping, and provision of services could still be large. Finally, the authors state that economic growth in the technology sector tends to be much more energy efficient than growth in other industrial and commercial sectors.

Jesse Ausubel:

Where Is Energy Going?

Inputs (Assumptions)

"Decarbonization" of the energy system (wood – coal – oil – gas – hydrogen)

Driven by demographics, transportability, electrification, environmental impact

Method

Analysis of world energy fuel mix and efficiency trends

Logarithmic plots of world fuel market share data

"Pulses" with increasing energy consumption per capita

Outputs (Energy Consumption & Fuel Mix)

1st pulse coal – 90% share by 1925

2nd pulse oil – 85% share by 1980

3rd pulse gas – projected transition fuel – 60% by 2030

4th pulse hydrogen – projected 60% share in 2100

Issues and Implications

Sources of natural gas and infrastructure

Development of fuel cell technology

Production of hydrogen – electrolysis with nuclear electricity?

SOURCE: RAND analysis.

Figure A.13— Ausubel

Ausubel. The paper by Ausubel argues that the emergence of cities increased energy consumption per capita and ease of transportation and storage made coal the fuel of choice. The higher energy density, pipeline transportation and easier storage drove the transition to oil. End use cleanliness and the transmission/ distribution grid drove electrification. It is argued that the lower emissions and flexibility to use in all sectors (direct combustion or in fuel cells) will make natural gas the transition fuel to hydrogen, the ultimate clean fuel.

Based upon data from the late 19th Century to the present, Ausubel identifies two "pulses" with rising world energy consumption per capita. The 1st pulse, the coal era, used 0.3-1.0 tons of coal equivalent (tce) per capita. The 2nd pulse, the oil era, which is argued to be currently waning, uses 0.8-2.3 tce per capita. Predicted are a 3rd pulse, the natural gas era (2000-2075), using 2.0-6.0 tce per capita, and a 4th pulse, the hydrogen era, beginning in the 2075-2100 time frame, using 6.0-15.0 tce per capita.

Estimates of the gas resource base have more than doubled over the past 20 years, and it is argued that development of the necessary transportation, distribution, and utilization infrastructure, including fuel cells, will be driven by

economic and environmental forces. Production of hydrogen from electrolysis is projected. Nuclear fission is proposed as the most efficient means to accomplish this at the scale needed to fuel a world hydrogen economy.

Amory Lovins and Brett Williams:

A Strategy for the Hydrogen Transition

Inputs (Assumptions)

Hydrogen represents clean source of energy for fuel cells

Fuel cell advancement will make hydrogen cells competitive in efficiency, price

Hydrogen transportation and storage problems will be addressed by technology

Method

Technological assessment of stationary fuel cell market leading to fuel cell adoption in cars, hydrogen transition

Focus on attaining competitive price, power, efficiency

Outputs (Energy Consumption & Fuel Mix)

Hydrogen grows rapidly as source of fuel in transportation, as well as buildings, possibly using PV as hybrid

Issues and Implications

Near-term focus on fossil fuel–powered fuel cells, particularly for stationary power, could provide long-range pathway for otherwise problematic hydrogen transition

SOURCE: RAND analysis.

Figure A.14— Lovins and William

Lovins and Williams. A report by Amory Lovins and Brett Williams asserts that hydrogen power for stationary fuel cells (e.g., for buildings) under a distributed generation scenario would reduce the size and cost of fuel cells, as well as hydrogen infrastructure, to the point where they would be cost-effective in automobiles, particularly in super-efficient "hypercars" of low weight and high mileage. Of course there remains the problem of hydrogen refinement and infrastructure construction. Even under the most optimistic scenarios these activities may not be competitive at the margin without aggressive policy intervention.

At the same time, the fact that fuel cell technology can continue to advance without relying on hydrogen in the near term makes it possible that the technology could be widely adopted, with methanol or natural gas as a transition fuel, before the political or economic antecedents of a hydrogen economy are worked out. Lovins and Williams assert that the development of a stable market for stationary, distributed power generation can provide a pathway for fuel cell technological improvement eventually enabling their use in mass-produced automobiles. Once fuel cell infrastructure has been established, a hydrogen transition would face fewer obstacles.

California Air Resources Board:

Status and Prospects of Fuel Cells as Automobile Engines

Inputs (Assumptions)

Fuel cell potential efficiencies higher than potential of existing fuels

Fuel cells cleaner in terms of SO_2, NO_x, and CO_2

Method

Technological assessment

Focus on attaining competitive price, power, efficiency

Survey of current research trends, best available projections of costs

Outputs (Energy Consumption & Fuel Mix)

Some increase in amount of natural gas used in near term

Possible eventual transition to hydrogen, but not by 2020

Issues and Implications

Increased dependence on natural gas

Need for additional sources of natural gas

Volatility of natural gas prices becomes economically more important

SOURCE: RAND analysis.

Figure A.16— CARB – Fuel Cells

CARB – Fuel Cells. The California Air Resources Board (CARB) study of automotive fuel cells examined the cost of building a hydrogen infrastructure in the United States, concluding that at present it was too high to make hydrogen a feasible fuel. CARB cited research conducted by Argonne National Laboratory showing that for a hydrogen economy equivalent to 1.6 million barrels of gas per day in 2030, capital costs were projected at $230-400 billion and distribution facilities at $175 billion. With optimistic fuel efficiency assumptions, this works out to $3500-5000 per vehicle, equivalent to $3.00 - $4.30 per gallon of gasoline (without the material and operational expenses). This cost is combined with the difficulty of storing hydrogen onboard, effectively ruling out hydrogen as a fuel source for automotive fuel cells in the near future. However, public sector transportation may be a viable near-term option, as there are several hydrogen-powered bus demonstration projects in the works worldwide.

CARB examined methanol and gasoline as a source for hydrogen. The study noted the need to chemically process gasoline (probably at refineries) before usage in fuel cells. At present methanol is a more likely candidate; a methanol infrastructure would be substantially less expensive than a hydrogen infrastructure, and could be in place in a matter of years if demand materialized.

A.D. Little:

Distributed Generation: Understanding the Economics

Inputs (Assumptions)

Utility deregulation and system capacity limits make distributed generation more attractive

Fuel cells, cogeneration, small gas turbines, microturbines, and enabling technologies (net metering) are making distributed generation (DG) more efficient, less costly

Method

Market study using data on fuel prices, cost of substituting various technologies, and ROI calculations

Outputs (Energy Consumption & Fuel Mix)

Little change in consumption over base cases

Increase in natural gas use (depending on technology choice)

Issues and Implications

Possible reliance on natural gas, increased importance of gas price volatility

Implications for industry standards, consumer protections for new distributed generation market

Potential for R&D allocations to support imminent commercialization of DG

SOURCE: RAND analysis.

Figure A.17— A.D. Little – Distributed Generation

A.D. Little – Distributed Generation. A business analysis conducted by Arthur D. Little demonstrates the potential benefits of distributed generation to power purchasers across the country. The ADL report provides a blueprint for analyzing the specific price factors that would lead to the adoption of distributed generation. These factors include local prices for natural gas and electricity, transmission and distribution costs, energy price volatility factors, investment horizons, and capital costs for distributed generation. The report demonstrates the need for examination of local business conditions when considering the viability of distributed generation.

Distributed generation is an issue for energy scenarios because of its potential impact on efficiency and fuel mix. Several firms are offering or preparing to offer stationary fuel cells. United Technologies has commercialized a 200 kW cell priced at over $1 million. Other firms are planning commercialization in the next few years, some for residential applications. The stationary cells now under development typically use natural gas for fuel. CO_2 emissions are reportedly less than half that of typical fossil fuel plants, and efficiencies could be in the over-40% range, particularly if distributed generation makes cogeneration more widespread. Higher efficiencies may be attained by the emerging solid oxide and

molten carbonate cells, which operate at higher temperatures than current proton exchange membrane (PEM) cells. Several firms are now working on grid-connected cells that, with deregulation, could make fuel cells more attractive. Early targets for stationary fuel cells will be businesses where high reliability and uninterrupted power are priorities, and where cogeneration is both feasible and attractive.

Energy Information Administration:
Future Supply Potential of Natural Gas Hydrates

Inputs (Assumptions)
- Methane gas trapped inside cage of water molecules
- Enormous resource on sea floor and in Alaskan permafrost
- World resource several orders of magnitude larger than conventional natural gas

Method
- Technology development for cost-effective extraction
- 2000 Methane Hydrate Research and Development Act

Outputs (Energy Consumption & Fuel Mix)
- Source of natural gas for 21st century transition fuel

Issues and Implications
- Possible release during extraction (methane 20X greenhouse effect as compared to CO_2)
- Experience in Arctic oil exploration allows hazard evaluation
- Availability of natural gas can greatly reduce CO_2 and other emissions

SOURCE: RAND analysis.

Figure A.18— EIA – Gas Hydrates

EIA – Gas Hydrates. If even a small fraction of methane hydrates can be extracted economically, natural gas would be a viable 21st century transition fuel. The 1995 USGS estimate is 200,000 Tcf of U.S. reserves, as compared with 1400 Tcf of conventional natural gas reserves. World figures are 400 million Tcf, as compared with 5000 Tcf of conventional reserves. Current world energy demand is equivalent to approximately 300 Tcf annually.

Extraction of the gas from hydrates requires development of technology to drill through the sea bed safely and cost-effectively. Experience with deep ocean commercial and research wells and in the Arctic provides a base of knowledge, and Japan, India and the U.S. are moving forward with R&D.

Hydrates are a two-edged sword. Warming climate could release limited amounts of potent greenhouse gas, and inadvertent or accidental releases could occur during exploration and extraction. However, hydrates could provide an enormous supply of methane which, when used as a combustion fuel or in fuel cells, could vastly reduce CO_2 emissions as compared to use of coal or oil.

KPMG:

Solar Energy: From Perennial Promise to Competitive Alternative

Inputs (Assumptions)

PV represents clean source of power

Price, technology are major barriers to widespread adoption

Method

Technological assessment

Focus on attaining competitive price, power, efficiency

Survey of current research trends, best available projections of costs

Outputs (Energy Consumption & Fuel Mix)

PV a major source of electricity for residential, commercial sectors by 2050, but not by 2020

Issues and Implications

Additional sources of cheap silicon may be required

PV may be best as hybrid for fuel cells (hydrogen refining) – or in certain regions

Question of whether visual profile, physical siting pose additional barriers to adoption

SOURCE: RAND analysis.

Figure A.19— KPMG - Solar

KPMG - Solar. The environmental organization Greenpeace has long been a proponent of large-scale investments in solar manufacturing. In support of this goal, in 1999 Greenpeace commissioned an objective economic analysis from KPMG's Economic Research and Policy Consulting bureau in the Netherlands on the economic feasibility of constructing a 500 MW power plant. (Presently, the Netherlands is projected to have an installed PV capacity accounting for 1.5% of electricity demand by 2020.)

The KPMG study examined four issues: the total area for siting of PV panels in the Netherlands, the total electricity possible by siting existing PV technologies on such surfaces, the present cost of PV (4 to 5 times market price in the Netherlands), size of subsidies likely to be offered for renewable electricity investment (18% of investment costs), potential energy savings of PV investment (21% of investment costs), and projected cost reductions obtainable from large-scale production.

The KPMG study found that manufacturing capacity of PV would have to increase 25-fold to bring the price of existing technology down to market levels. Furthermore, the KPMG study cast some doubt on the supply of silicon, which is

used in conventional PV. (Silicon prices have been volatile, and world supply is sufficiently limited to make large-scale PV manufacturing essentially reliant on silicon availability.) Finally, the KPMG study found that 18% of the Netherlands' electricity generation could be provided by solar were all of its residential roof area converted to PV, with commercial buildings offering less potential area. However, the KPMG study also found that the construction of a 500 MW solar power plant would be feasible, and that such a plant would bring solar energy prices to Euro .16 per kWh, close to the market rate of Euro .13 per kWh.

National Renewable Energy Laboratory:

Photovoltaics: Energy for the New Millennium; The Federal Wind Energy Program; DOE Biomass Power Program: Strategic Plan 1996–2015; Strategic Plan for the Geothermal Energy Program

Inputs (Assumptions)

- **PV, wind, biomass, and geothermal energy represent clean sources of power**
- **Price, technology are major barriers to widespread adoption**

Method

- **Qualitative examination of myriad of roadblocks and technological hurdles facing renewables industry**
- **Focus on bringing technology to cost-effectiveness, market**

Outputs (Energy Consumption & Fuel Mix)

- **Modest change in fuel mix, consumption by 2020 – large potential change in later years**
- **Potential for larger change in fuel mix if technological breakthroughs come to pass**

Issues and Implications

- **Possibility that increased R&D could bring about breakthrough, dramatic change in energy picture**
- **Possibility of increased distributed generation, with implications for transmission and distribution system**

SOURCE: RAND analysis.

Figure A.20— NREL – Photovoltaics, Wind, Biomass, and Geothermal

NREL – Photovoltaics, Wind, Biomass, and Geothermal. The National Photovoltaics Program plan suggests that continued growth rates of PV shipments imply an installed capacity in 2020 of 3-7 GW. In the last 5 years, growth rates have been on the order of 20%, and 25% may be feasible. The program also expects manufacturing capacity to grow seven fold and manufacturing costs to fall by 50%. However, system costs are projected to decline more slowly, to $4-8/W in 2005 and $1-1.5/W in 2020-2030. All of these projections are subject to wide uncertainties.

The PV Technology Roadmap Workshop identified a multitude of barriers to adoption of PV technology. These included high cost, low efficiencies, unfocused research and investment decisions (e.g. "lack of conviction to a technology choice"), weak infrastructure, cost of raw material, lack of cheap and reliable power inverters, low public exposure to and interest in PV, and unattractive appearance of PV. The Industry-Developed PV Roadmap projects PV capacity to rise to 10% of U.S. generating capacity in 2030, assuming an optimistic 25% industry growth per year. Under this scenario, 15 GW of installed peak capacity power would be provided by PV in 2020, with costs falling to $3.00/W in 2010 to $1.50/W in 2020.

The Federal Wind Energy Program, in collaboration with industry, utilities, universities, and other interest groups, seeks to develop the technologies to lead the world in cost effective and reliable wind power. By 2002, they aim to develop advanced wind turbine technologies capable of reducing the cost of energy from wind to $0.025 per kilowatt-hour (kWh) in 15-mile-per-hour (6.7-meters-per-second) winds. By 2005, they hope to establish the U.S. wind industry as an international technology leader, capturing 25% of world markets. And By 2010, the goal is to achieve 10,000 megawatts of installed wind-powered generating capacity in the United States.

The DOE Biomass Power program estimates that the potential exists for biomass power to grow by 2020 into an industry of 30,000 megawatts of capacity and producing 150-200 billion kilowatt-hours in the next twenty years. The program considers social, political, and environmental factors that would increase the adoption of biomass power, including the enforcement of landfill diversion rules, which would ensure clean materials are either recycled or reused as fuel; the employment of agricultural field residues as fuel; and finally the increase in efficiency of the biomass-to-energy process. An early strategy is the increase in biomass fuels in cofiring with coal plants, offsetting greenhouse gas emissions and producing electricity at a relatively high efficiency (>35%).

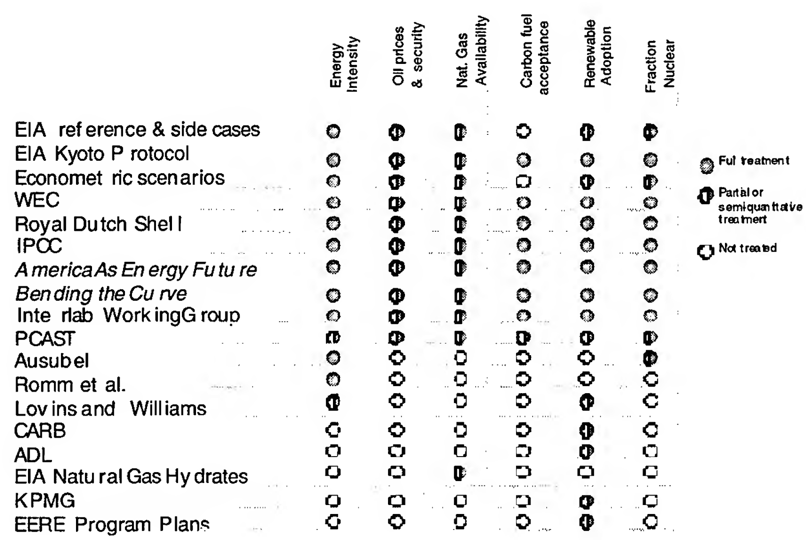
The DOE's Office of Geothermal Technologies (OGT) has five strategic goals that define the role geothermal energy has the potential to play this coming decade. OGT discusses the ability of geothermal energy to supply electrical power to 7 million homes (18 million people) in the U.S. by 2010, and to supply the basic energy needs of 100 million people in the developing world with U.S. technology through the installation of at least 10,000 megawatts of generating capacity by 2010. Another OGT strategic goal is the development of new technology by 2010 do meet 10 percent of U.S. non-transportation energy needs in subsequent years. Over the next decade, potential benefits of increased geothermal use include a reduction of U.S. carbon emissions by 80-100 million metric tons of carbon (MMTC) and global emissions by 190-230 MMTC, stimulation of investment in geothermal facilities both at home and abroad, and 1.6 million person-years of new employment opportunities.

Analysis Across the Scenarios

The level of detail with which the various scenarios treat the major uncertainties described previously is indicated in the figure below. A full quantitative treatment is indicated by a filled circle, a partial or semi-quantitative treatment by a half-filled circle, and lack of treatment by an unfilled circle.

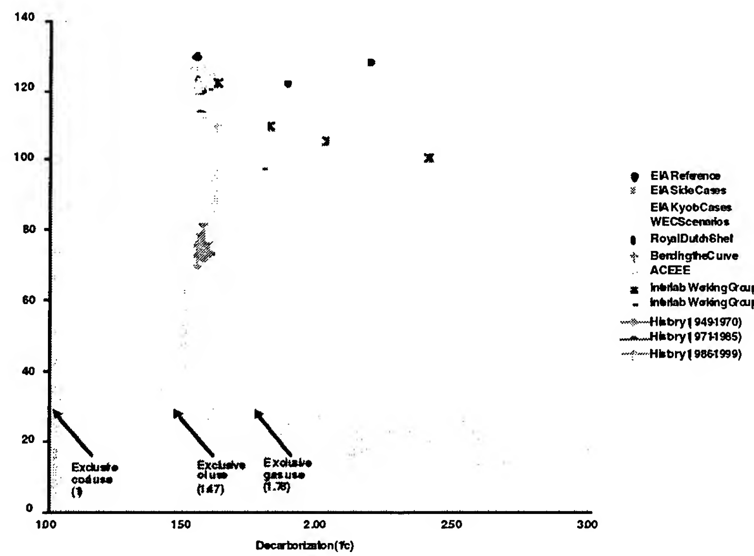
All of the full scenarios treat energy intensity in a quantitative manner, and most treat the acceptance of a carbon-intensive fuel mix quantitatively with some sort of CO_2 reduction strategy. The EIA Reference and Side Cases and the econometric scenarios are exceptions; CO_2 emissions levels simply follow from the calculated energy consumption and fuel mix for these scenarios. All of the quantitative scenarios treat the rate of adoption of renewable technologies and nuclear power quantitatively, however the EIA and econometric scenarios use a narrower set of assumptions leading to little increase in renewable energy by 2020 and close out the nuclear option via on-schedule decommissioning (partial treatment). All quantitative scenarios treat oil and natural gas supply partially in that none consider oil supply security or natural gas availability.

The PCAST scenario provides estimates of fossil fuel reductions arising from more rapid adoption of renewable technologies, and also considers the possibility of continued and expanded use of nuclear power, thus treating all of the uncertainties semi-quantitatively.



SOURCE: RAND analysis.

Figure A.21—How Uncertainty Was Addressed in Each Scenario



SOURCE: RAND analysis.

Figure A22—Energy Consumption vs. Decarbonization (quadrillions of BTUs)

Both Romm et al and Ausubel provide quantitative estimates of energy efficiency. The EIA report on methane hydrates addresses natural gas availability semi-quantitatively. Lovins and Williams address energy efficiency and renewable adoption quantitatively, but within a partial scenario. The technology-specific scenarios address the rate of renewable adoption semi-quantitatively, or quantitatively within a partial scenario.

To assess the policy implications of the various scenarios, in particular with respect to EERE's mission areas of clean energy and energy efficiency, it is useful to visualize the results of the analysis on three graphs: (1) U.S. energy consumption in 2020 vs. the inverse of the carbon content of the fuel mix in 2020; (2) U.S. energy consumption in 2020 vs. $ GDP/MBTU in 2020; and (3) the inverse of the carbon content of the fuel mix vs. $GDP/MBTU.

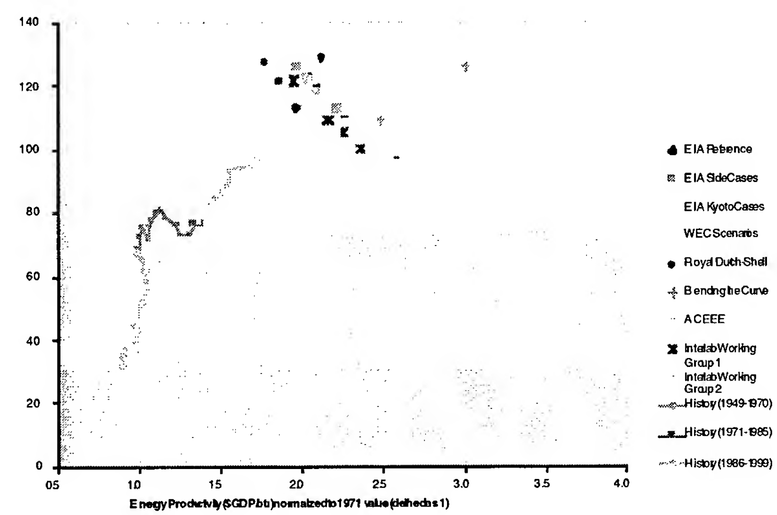
The graph above is a plot of U.S. energy consuption in 2020 in quadrillion BTU vs. the inverse of the carbon content of the fuel mix (1/C) for nine of the 14 quantitative scenarios. (The IPCC scenario did not have detailed fuel mix data needed for this plot, and the fuel mix details for the econometric scenarios of IEA, GRI, AGA, and IPAA were unavailable.) The decarbonization parameter

(1/C) was computed for each scenario.[4] The weight factors reflect the CO_2 emissions per quad of each fuel when burned, as reported by the EIA.

The vertical lines on the graph indicate the position on the horizontal axis of each fuel, if it were used exclusively. Thus, motion to the right represents the transition to a cleaner fuel mix, e.g., from coal to oil to natural gas to renewable and nuclear energy. The scenarios fall into two groups with respect to this transition:

The EIA Reference and Side cases, the DRI and WEFA econometric scenarios, Bending the Curve, the WEC High Growth (2 of 3) and Medium Growth variants all show little or no fuel mix change from 1998-2020.

The EIA Kyoto, WEC High Growth (1 of 3) and Low Growth variants, Royal Dutch-Shell, Interlab Working Group, and ACEEE scenarios all show substantial movement toward a cleaner fuel mix by 2020.



SOURCE: RAND analysis.

Figure A.23—Energy Consumption vs. Energy Productivity (quadrillions of BTUs)

[4] The decarbonization parameter was computed as the inverse of: C = [1/T] * [C*WC + O*WO + G*WG], where T is Total Consumption, C, O, and G are Coal, Oil, and Gas Consumption, respectively, and WX the weights for carbon emissions; WC = 1.00, WO = 0.68, and WG = 0.56.

The graph above is a plot of U.S. energy consumption in 2020 in quadrillion BTU vs energy productivity, as estimated by constant dollars of GDP per million BTU[5], for 8 of the 14 quantitative scenarios. (The data on energy productivity were unavailable for the 6 econometric scenarios.)

The scenarios portray a range of energy productivity; however, most scenarios fall into the range of 20-60% increase from 1998-2020. This group of scenarios also shows a wide range of energy consumption in 2020, from slightly less than 1998 to a 40% increase.

A few scenarios, in particular, the WEC Low Growth variant, and the ACEEE and Bending the Curve scenarios, show much larger increases in energy efficiency. For WEC and ACEEE, this is accompanied by greatly reduced energy consumption, while for Bending the Curve, energy consumption is slightly larger than that of the DOE Reference Case.

Analysis of Scenario Clusters

These scenarios reflect the underlying tension between the efficient use of energy to drive our economy and enhance our quality of life, and the detrimental impact that energy generation has on the local and global environment. Total energy consumption was a basic descriptor for all the complete scenarios we have assessed, but there were no common metrics for the impact on the environment. To provide such a common measure that could be used to compare scenarios RAND developed an index of emissions and applied to carbon emissions as a surrogate for overall impact on the environment. In this metric the inverse carbon content of the fuel mix and $ GDP/MBtu were used in combination to provide an overall measure of environmental effect due to energy use. The derivation of this metric is shown in the highlight box, which also explains why this combination of parameters provides a surprisingly complete single metric for environmental impact.

[5] Constant 1996 dollars have been used throughout this report.

The energy productivity parameter, P, is defined as:

$$P = \$GDP / E \qquad (1)$$

Where E is defined as total energy consumption.

The carbon emissions parameter, C, is defined as:

$$C = \frac{t_o E_o + t_g E_g + t_c E_c}{t_c E} \qquad (2)$$

where

t_o = tons carbon/MBtu oil; E_o = total oil consumption

t_g = tons carbon/MBtu gas; E_g = total gas consumption

t_c = tons carbon/MBtu coaoil; E_c = total coal consumption

In terms of these parameters, the total carbon emissions, T, can be computed as:

$$T = C t_c E \qquad (3)$$

Using the definition of P, we can rewrite (3) as:

$$T = \frac{C t_c \$GDP}{P} \qquad (4)$$

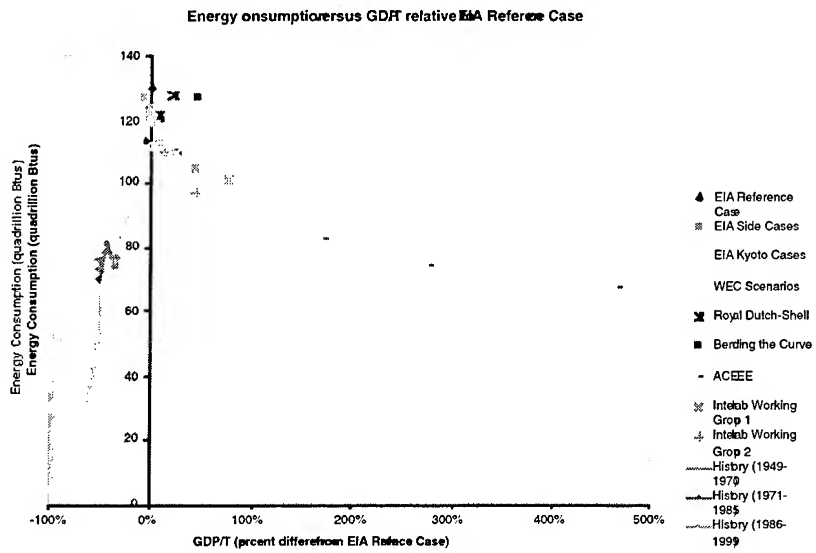
which is equivalent to:

$$P\left(\frac{1}{c}\right) = t_c\left(\frac{\$GDP}{T}\right) \qquad (5)$$

Thus, the product of the decarbonization and energy productivity parameters is proportional to the quantity \$GDP/T, which is the carbon CO_2 emission analog of the energy productivity parameter and may thus be defined as carbon productivity. The constant of proportionality is the tons of carbon per MBtu of coal burned. This quantity has been roughly constant at slightly more than .025 metric tons per MBtu of coal burned since 1951.[6]

SOURCE: RAND analysis.

[6] Marland, G., Andres, R. J., and Boden, T. A., *Global, Regional, and National CO_2 Emissions Estimates from Fossil Fuel Burning, Cement Production, and Gas Flaring: 1950-1994 (revised February 1997)*, ORNL/CDIAC NDP-030/R7, electronic data base.



SOURCE: RAND analysis.

Figure A.24—Energy Consumption vs. Carbon Productivity (quadrillions of BTUs)

Using this metric (i.e., carbon productivity) and total energy consumption we are able to compare and contrast the individual scenarios in terms of energy use and environmental impact. In the above graph, energy consumption is plotted against carbon productivity. This graph illustrates that the scenarios can be grouped into four clusters for the purposes of our analysis.

Several of the scenarios cluster around the EIA Reference Case, demonstrating that their range of assumptions do not vary sufficiently from linear extrapolations of current trends and policies to inform policy. These form the first grouping.

The higher growth Royal Dutch Shell Scenario and one of the Bending the Curve and WEC/IIASA high growth variants from a second cluster with similar energy consumption and somewhat lower carbon emissions per unit of GDP.

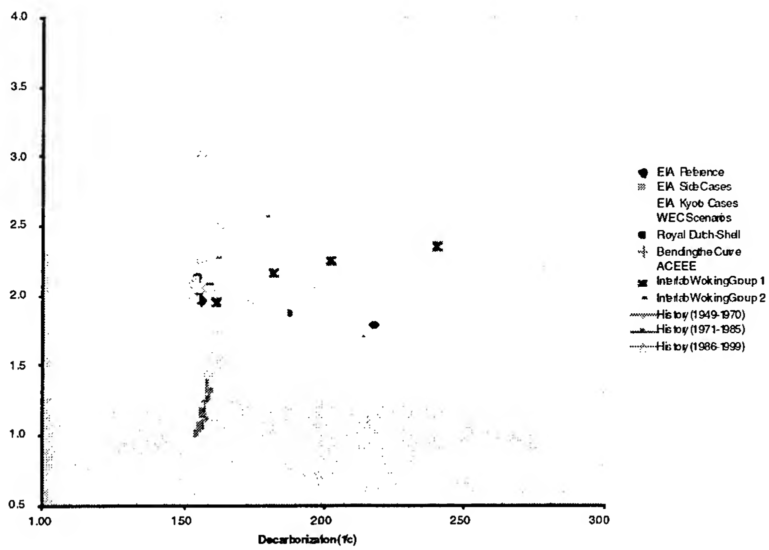
The EIA Kyoto and Interlab Working Group scenarios represent similar reductions in carbon emissions per unit of GDP, together with reduced energy consumption (relative to the EIA Reference Case), achieved via a combination of carbon tax or trading incentives, and clean/efficient technology adoption. The low growth versions of Bending the Curve and WEC/IIASA also fall near the boundary of this cluster of scenarios.

The WEC/IIASA low growth scenarios and the scenarios from the report, America's Energy Choices (ACEEE et al) fall in regions of the graph relatively far removed from the other three clusters, with substantial reductions in carbon emissions per unit of GDP and energy consumption, again relative to the EIA Reference Case. These form the fourth grouping.

The two sets of scenarios from the Inter-Laboratory Working Group both show considerable variation in energy consumption and GDP per unit carbon emissions. The Interlab Working Group's more advanced scenarios involve energy consumption at levels near that experienced today, with substantially lower carbon emissions per unit of GDP than experienced at present.

Of particular note is information that was *not* included in the scenarios we assessed. Our energy history has been characterized by unanticipated economic or political disruption resulting from exogenous events. Events such as a Middle East war, environmental catastrophe (tied by either perception or reality to increased carbon emissions), or a worldwide economic recession all provide sufficient potential for such disruption. Since our intent is to cover the range of possible scenarios, not predict the most likely scenario, it is important to include scenarios that consider situations in which the U.S. is once again forced into an energy crisis. Adequate consideration of scenarios that include disruption can motivate explicit policy regard for unanticipated events.

Improvements in the technology associated with energy use can increase the efficiency with which we use energy and enhance its productivity. In this study, we use the ratio of GDP produced to BTUs used by the U.S. as the surrogate for this measure. We refer to this as *energy productivity* to emphasize the fact that it includes more than the simple efficiency of electrical devices. Importantly this includes the sophisticated production and use choices that are increasingly available to us because of information technology – such as avoiding the production (and energy waste) of excess inventory or using automated control of heating and air conditioning in the home. Technology improvements can also allow us to find and use less carbon intensive sources for our energy (estimated here, resulting in lower environmental impact). In the figure below we plot energy productivity vs. decarbonization to provide some sense of which of these uses of technology is reflected in each of the scenario clusters.



SOURCE: RAND analysis.

Figure A.25—Energy Productivity vs. Decarbonization (GDP $/MBTU)

The EIA Reference cases (and related scenarios) rely importantly on improvements in energy efficiency and productivity, the EIA Kyoto scenarios rely on a mixed use of technology reflecting both productivity enhancements and decarbonization, and the Royal Dutch-Shell scenarios reflect a substantial move toward low-carbon energy sources. All of these scenarios reflect substantial improvements that are roughly similar to the improvements we have observed historically, especially in energy productivity. The fourth group, typified by the WEC/IIASA low growth scenarios and ACEEE report, stand in marked contrast to these in that they require combinations of improvements in energy productivity and low carbon energy sources that are substantially beyond recent historical experience.

Analysis of Meta-Scenarios

Meta-Scenarios as Alternative Futures for Policy Planning

Using a common framework to analyze the individual scenarios revealed that they fell into distinct clusters that were sufficiently different from one another to reflect importantly different policy challenges and implications. In essence, the individual scenarios represented variants of a few *meta-scenarios* that could serve usefully as the alternative futures necessary for robust policy assessments and

planning. The existing individual scenarios commonly used for planning in the energy community can be summarized as variants on four meta-scenarios. While the four do cover a broad range of alternative futures, we argue that this range is not broad enough for robust policy planing. A meta-scenario characterized by slow economic growth and relatively low energy consumption (compared to the EIA Reference Case) was added to complete the set. It is of note that this scenario (which we term *Hard Times* in the section to follow) is not well-represented by any of the planning scenarios we reviewed.

Five Meta-Scenarios

The five meta-scenarios that resulted from our analysis are detailed below and summarized in Table 2. (Parameters in Table 2 are increases and decreases with respect to *Business-as-Usual.*)They are specified by the sociopolitical, economic, and energy parameters we have developed to define a common framework to compare and contrast scenarios. They are arrayed according to a rough characterization as to their economic growth rate and their impact on the environment.

Hard Times (Low Growth – Moderate Environmental Impact). Either economic downturn or supply constraint or environmental catastrophe or combination leads to low to zero energy growth and no new technology, which also means very slow productivity growth and same fuel mix. None of the full energy scenarios fall in this category, because they do not consider surprises or discontinuities.

Business-as-Usual (Moderate Growth – High Environmental Impact). Extrapolation of current trends, i.e., energy growth with continued improvement in energy productivity, but fuel mix actually becomes slightly more carbonized because nuclear is decreasing and all the fossil fuels are increasing. This is a set of scenarios clustered around the EIA *Annual Energy Outlook 2000* results.

Technological Improvement (Moderate Growth – Low Environmental Impact). Improvements in productivity and/or decarbonization resulting from use of improved technology lead to moderate economic growth with much smaller growth in energy consumption. The EIA Kyoto and both Interlaboratory Working Group full scenarios fall in this category.

High Tech Future (High Growth – Moderate Environmental Impact). Economic and energy growth similar to *Business-As-Usual*, but with technological advances that provide for productivity or decarbonization improvements like *Technological*

Improvement. The Royal Dutch Shell Sustained Growth scenario, and one of the World Energy Council High Growth scenarios.

New Society (Low Growth – Benign Environmental Impact). Environmentally conscious and energy efficient choices in technology and life style lead to much higher productivity, much higher decarbonization, and decreased energy consumption (e.g., total energy consumption in 2020 like that of 1960). The ACEEE and WEC Low Growth full energy scenarios fall in this category.

Pathway Analysis

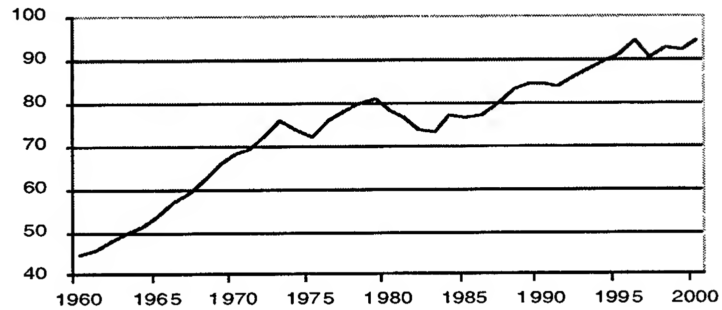
Each meta-scenario is described in terms of the sociopolitical, economic, and energy parameters that dominate possible pathways from the present to the future envisioned by these scenarios. Where appropriate, the historical path experienced by the U.S. is compared to the path that we would need to follow to find ourselves in the future corresponding to each meta-scenario. *Signposts* (e.g., in 2010) indicating that we are on this path are identified, and *shaping strategies* (i.e., positive actions to increase the likelihood of this path) and *hedging strategies* (i.e., positive actions to mitigate impacts of this path) are discussed.

U.S. Energy History. The Energy Information Administration (EIA) publishes a yearly Annual Energy Outlook, as well as an Annual Energy Review. The latter includes the document, *Energy in the United States: A Brief History and Current Trends.*[7] This serves as the basis for the analysis in this section.

As shown in Figure A.26, U.S. energy consumption has grown substantially over the past forty years, but not monotonically. Rapid growth between 1960 and 1972 ended during the oil crisis of 1973, and energy consumption fluctuated between 72 and 80 quads during the period 1972-1985 (which included times of high oil prices and economic recession). Energy consumption has increased since 1985, but again not monotonically, and at a slower rate than in the 60s and early 70s.

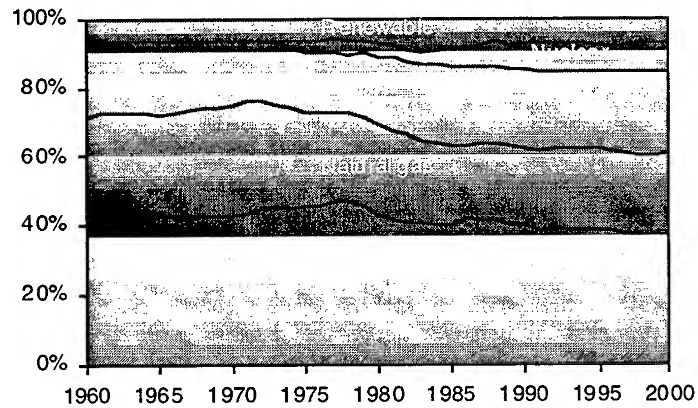
As shown in Figure A.27, the U.S. fuel mix is dominated by fossil fuels, with oil comprising about 37% since 1960. The natural gas component peaked in 1971 and has stabilized at 24%, coal reached a minimum in the 70s, then rebounded to its current level of 23% around 1985. Renewable energy has remained constant at about 7% since 1960, and the nuclear contribution has been 8% since the mid-1980s. There has been little change in the fuel mix for the past 15 to 20 years.

[7] This is available at http://www.eia.doe.gov/emeu/aer/eh1999/eh1999.html



SOURCE: EIA.

Figure A.26—U.S. Energy Consumption (quadrillion BTUs)



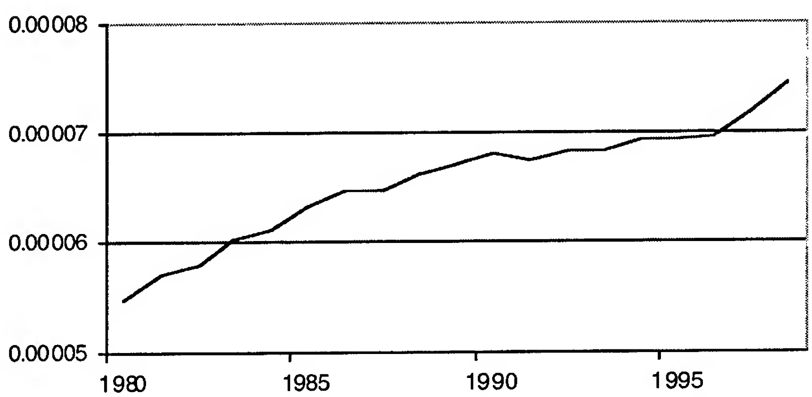
SOURCE: EIA.

Figure A.27—U.S. Fuel Mix (percent)

As illustrated in Figure A.28, energy productivity, approximated by the ratio of dollars of gross domestic product (GDP) to BTU of energy consumed, has been monotonically increasing since the 1970s. In 1980 the U.S. had $54 in GDP per million BTUs; the value in 1998 was $74.50. The average yearly increase has been 1.8% over the past 18 years.

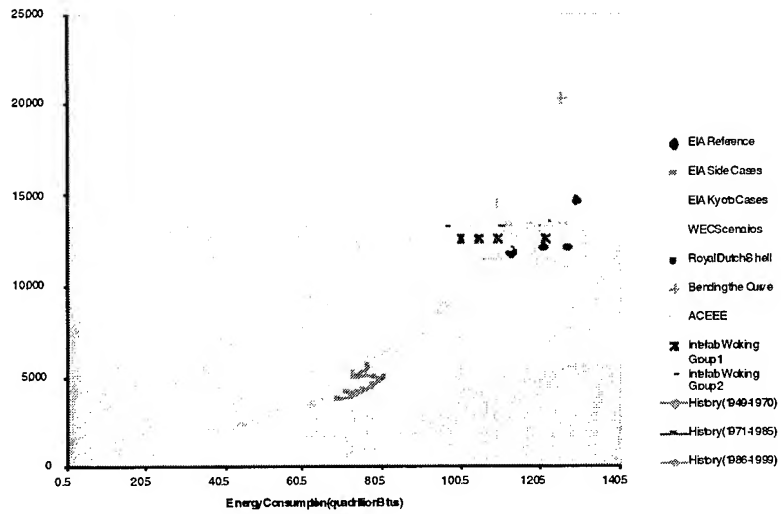
Figure A.29, which graphs historical data (WWII to the present) for U.S. energy parameters, suggests that there are several periods during which our energy use changed in ways that will be instructive for our scenario analysis. These periods are:

- 1949-1960: rapid growth with periods of substantial decarbonization;
- 1960-1973: rapid growth without energy productivity improvement;
- 1974-1984: energy productivity improvement without growth;
- 1985-2000: growth with energy productivity improvement and decarbonization.



SOURCE: EIA.

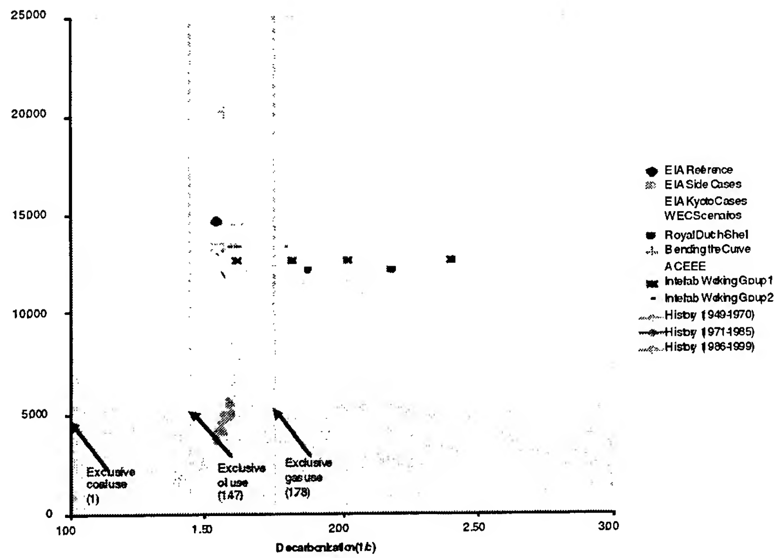
Figure A.28—U.S. Energy Productivity ($ GDP per BTU)



SOURCE: RAND analysis.

Figure A.29—GDP vs. Energy Consumption ($ billion)

Figure A.29 illustrates that although GDP growth is generally linked to energy consumption, it is not immutably so. There have been limited periods (typically proceeded by strong exogenous pressures) during which the economy grew without similar growth in consumption and the long term trend seems to be toward greater economic growth coupled with lesser associated energy consumption.

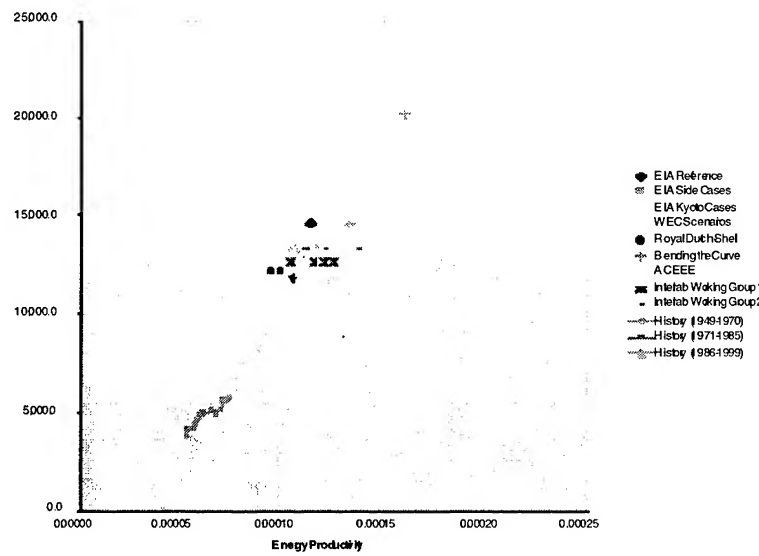


SOURCE: RAND analysis.

Figure A.30—GDP vs. Decarbonization

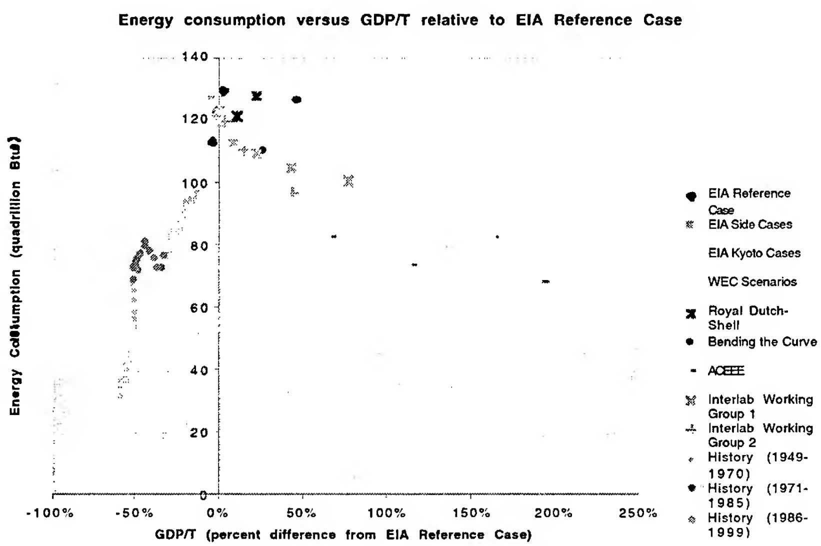
Figure A.30 shows a long-term trend that illustrates that substantial change in the nation's fuel mix will be a challenge. It does illustrate that there have been times in the past where substantial movement in this arena has taken place.

The period from 1949 to 1973 was a period of monotonic increases in U.S. energy consumption as the economy grew. The history reflects a large change in decarbonization before 1970 (due to the switch from coal to oil and gas), and almost the entire energy productivity improvement occurring since 1970. Because such shifts are dependent on the rate of change of the underlying infrastructure as well as the carbon characteristics of the fuels used, the change during this period is surprising as to its rapidity and provides some insights as to how quickly such shifts can take place if the proper economic incentives are in play.



SOURCE: RAND analysis.

Figure A.31—GDP vs. Energy Productivity ($ billion)



The graph of GDP vs. Energy Productivity provides insights into how quickly energy productivity (or energy efficiency) can increase in times of economic stress due to energy prices. Although the long-term trend has been very much

the same over the half-century covered by the chart, there have been periods in which dramatic movement (both positive and negative) has taken place.

In the late 1960s, low energy costs motivated in a *decrease* in the productivity of energy use. Shortly thereafter, the energy crisis of 1973 caused a dramatic decrease in fuel supply, with accompanying economic disruption. The next several years were a period of adjustment during which curtailment or "belt-tightening" was followed by price- and policy-driven improvements in the energy efficiency of infrastructure and changes in consumption patterns (e.g., abundance of smaller automobiles).

By 1984, energy consumption was similar to that of a decade earlier, but energy productivity had increased substantially. Growth in energy consumption resumed in 1984. This growth continues to the present day, albeit together with growth in energy productivity and decarbonization. As oil prices decreased, the economy flourished and the U.S. abandoned its efforts toward energy independence or lowering its reliance on oil.

In summary, the period prior to 1960 was characterized by a change in the carbon content of the fuels used to generate the nation's energy and so is instructive in considering future efforts to decarbonize. The period 1960-1973 had substantial growth in energy consumption without any improvement in energy productivity, primarily because energy was cheap. The period 1974-1984, following the Arab Oil Embargo, was a time of little to no growth in energy consumption and substantial increase in energy productivity, because of a combination of energy shortages, energy price increases, energy conservation policies, and slow economic growth. The period from 1985 to the present had growth in both energy consumption and energy productivity, driven by a combination of a strong economy, technological improvements, and environmental and consumer activism.

Thus, U.S. energy history is one of growth, crisis, adjustment, and more growth, this time together with movement toward clean energy and energy efficiency. This suggests that energy scenarios need to consider both the effects of potential crises and the possibility that growth in energy consumption continue.

Note that there is historical precedent for decarbonizing and improving energy productivity at the same time, as might be envisioned in the future, e.g., with technologies such as hybrid electric vehicles and (hydrogen) fuel cells.

Hard Times. *Hard Times* (100 quads in 2020) is similar to what happened to us before (1973-1984), and there are many possible events that could trigger this sort of slowdown in energy use without much improvement in energy productivity

either (90 $/MBTU), e.g., Middle East war, environmental catastrophe(s) tied either by perception or reality to increased carbon emissions, worldwide economic recession.

Signposts: No energy growth, little productivity growth, stagnant economy.

Shaping Strategies: We don't want to go to this future, but inadvertent shaping strategies might include: heavily increased regulatory constraints on energy development; removal of incentives for increased energy productivity; flawed policies leading to economic recession.

Hedging Strategies: Increased R&D of energy productivity and renewable energy technologies; incentives for energy productivity and decarbonization; incentives for oil and gas exploration; relicensing of nuclear power plants.

Business-as-Usual. Note that there are many obstacles to reaching the *Business-As-Usual* future. This meta-scenario, with total energy consumption of 112-129 quads and decarbonization of 1.5-1.6 in 2020, assumes that we will continue, simultaneously, to increase our oil imports, increase our use of natural gas (e.g., for essentially all new electric capacity additions), while using more coal, decommissioning nuclear plants on schedule, and making little progress on renewable adoption. Price and security of oil supply, price and adequacy of gas supply, and acceptability of higher levels of carbon emissions are all uncertainties that could derail this extrapolation, especially with respect to the economic and sociopolitical parameters, e.g., through disruption, or by decreasing GDP growth, increasing the energy contribution to CPI, and increasing the cost of health and environmental impacts and regulatory compliance. It is important to note that from 1973-1984, a combination of supply constraints and economic downturn kept energy growth constrained. Moreover, since 1985, we have been increasing our energy productivity, and this trend will likely continue, to the extent that we continue to employ new technology, at least at the replacement rate.

Signposts: Continued growth in energy demand with productivity increasing at current rate, and decarbonization remaining constant or decreasing by 2010.

Shaping Strategies: Incentives for increased oil and gas exploration, support for emissions trading strategies.

Hedging Strategies: Increased R&D of energy productivity and renewable energy technologies; incentives for energy productivity and decarbonization; relicensing of nuclear power plants.

Technological Improvements. *Technological Improvements* has several different possible pathways. Because the energy growth is modest (97-110 quads), paths include going through a period of *Hard Times*, which is similar to the historical path to 2000. It also requires changes in productivity (105–133 $/MBTU) and decarbonization (e.g., 1.6-1.8 for the 2000 Interlaboratory Working Group) that are not too different from what we have seen in our history. For example, we might imagine that environmental impact takes a more central stage, via events just short of what would put us into *Hard Times*, or that would only put us there briefly, but with sufficient economic growth (i.e., 2.2%/year) that we have the wherewithal to do something about it (via technology and/or economic intervention, e.g., via emissions trading). The main point when comparing *Technological Improvements* to *New Society*, is that the rate of turnover may be sufficient here if we have economic growth and a mandate for improved productivity and clean fuels. Or, we might find that supply constraints have forced us to move in this direction, e.g., incentives for gas production insufficient to supply the demand for new electric plants, industry, and buildings, or oil imports not anywhere near the level projected by EIA, together with environmental constraints on new exploration in the U.S. Then we might become even more efficient in our use of energy, like we did in the 1970s and continuing to the present.

One possible business-as-usual pathway from the present might pass through a period in which there is little or no growth in energy consumption, but substantial energy productivity increase (e.g., 2000-2010). This might happen, for example, because of supply constraints or an environmental problem short of what it would take to put us into the *Hard Times* scenario. Within a business-as-usual set of assumptions, productivity would continue to improve at about the current rate, or perhaps somewhat faster to maintain some level of economic growth. Under this scenario, recovery of fuel supplies or solution of the environmental problem, e.g., with new technology, might enable continued growth in both energy consumption and energy productivity (e.g., 2010-2020), much as has happened since 1985. The sociopolitical and economic parameters of such a scenario would depend strongly on the details of the pathway.

Signposts: Signposts would include near-term fuel shortages or greatly underestimated environmental impacts. A "glitch" in energy growth lasting more than a year or two, together with increased implementation of new energy technologies (e.g., hybrid vehicles, microturbines).

Shaping Strategies: Incentives for energy productivity and decarbonization. Inadvertent shaping strategies might include rapidly escalating fuel prices or infrastructure failures.

Hedging Strategies: Hedging strategies include incentives for oil and gas exploration, relicensing of nuclear power plants, increased R&D of energy productivity and renewable energy technologies, and incentives for energy productivity and decarbonization.

High Tech Future. The *High Tech Future* has a combination of challenges, in the sense that it requires energy growth like *Business-As-Usual*, (120-127 quads) along with improvements in the fuel mix and energy productivity approaching those that we will describe in the *New Society* scenario below (decarbonization of 1.6–1.9 and energy productivity of 112–144 $/MBTU). So, to get there, one must postulate overcoming many of the obstacles to energy supply described under *Business-As-Usual*, while also accomplishing some change in the way we use energy. However, because there is higher economic growth (3.2%/year), perhaps one can envision economic growth spawning large and rapid technical change and equipment turnover.

Signposts: Continued economic prosperity leading to higher economic growth, increasing rate of adoption of new technology (e.g., hybrid vehicles), abundance of cheap oil and gas.

Shaping Strategies: Incentives for oil and gas exploration; R&D incentives and subsidies for energy productivity and renewable energy technologies; relicensing of nuclear power plants.

Hedging Strategies: Increased R&D of energy productivity and renewable energy technologies; incentives for energy productivity and decarbonization.

New Society. Note that in order to reach the *New Society* we have to do something we never have done before, i.e., **reduce** energy consumption (from approximately 100 quads to 675-83), and also that the scale of the productivity and decarbonization improvements are daunting compared to those of the past, even with the downturn in economic growth embodied in this scenario. (Energy productivity has increased from 54 $/MBTU to 92 in the past 40 years, an average of 1.8%/year. New Society requires an increase from 92 to 150–192 in the next 20 years, an average of 3.1-5.6% per year. Decarbonization has increased from 1.49 to 1.62 over the past 40 years, an average of 0.2% per year. New Society requires an increase from 1.62 to 1.8-2.6 in the next 20 years, an average of 0.5-2.3% per year.) In order to achieve reduced energy consumption **and** a less carbon-intensive fuel mix at the same time, we will need to change the manner in which we use energy in a revolutionary way. Technologies such as fuel cells, photovoltaics, electric and hybrid vehicles are presently much more expensive than our currently used alternatives. We would need to allocate very large resources to pay these costs, e.g., in the form of increased fuel taxes, increased

R&D costs, and increased subsidies for energy productivity and renewable energy technologies. If successful, we would obtain health and environmental benefits from decreased energy use and use of cleaner energy technologies. A more complete analysis of this meta-scenario should evaluate the rate of turnover of energy conversion and utilization equipment, infrastructure improvements and modifications (e.g., electricity storage) and the possible time to implement any necessary lifestyle changes (e.g., land use, public transportation, work patterns) to see how difficult it might be to actually get there in 20 years.

Signposts: Revolutionary increases in energy productivity and decarbonization; accelerated use of renewable energy technologies; lifestyle changes involving greater use of mass transit, less driving, load-leveling electricity use.

Shaping Strategies: Major emphasis and resources devoted to energy productivity improvement and accelerated adoption of renewable energy technologies, including incentives, subsidies, and public education.

Hedging Strategies: Incentives for oil and gas exploration, R&D on clean coal technologies, relicensing of nuclear power plants.

Issues and Policy Implications

Issues

There are 7 major issues identified by this scenario analysis:

- Need to explore pathways to implementation of scenarios, especially those that lead to a cleaner fuel mix and more efficient energy consumption.
- Need to explore the effect of "surprises" leading to either economic or energy supply disruptions, such as have occurred in the past (e.g., the period 1974-1984). This should include a new source of surprises, technology.
- Implications of no significant change in the U.S. fuel mix to 2020, in particular, increased use of coal.
- Oil price and supply security, and alternative oil and liquid fuel supply options.
- Natural gas price and availability, especially within North America, and required level of LNG imports.
- Need to explore the policy actions needed to increase the rate of adoption of renewable energy technologies.
- The future role of nuclear power in the electricity fuel mix.

The policy implications and insights for EERE planning derive directly from these issues.

Policy Implications

Many of these issues directly relate to DOE/EERE's strategic planning and involve the policy instruments inherent in its programs and initiatives (see Box on following page). The specific insights of importance to these efforts are discussed below.

RAND's scenario analysis examined a range of full scenario outputs which included total energy consumption, energy efficiency, and decarbonization. With respect to decarbonization, the scenarios fell into two groups: one that showed minimal change from the EIA Reference Case, and one that showed gains in decarbonization resulting from a variety of technical, policy, and social assumptions. Regarding energy efficiency and total energy consumption, the scenarios examined display a relatively wider variety of possible outcomes, resulting from policy change as well as economic change and dramatic gains in energy efficiency.

Although planning scenarios were classified as "full" if they provided quantitative estimates of total energy, decarbonization, and efficiency to 2020, these variables alone are not sufficient to illuminate the range of options available to policy makers, or the range of uncertainties facing America's energy picture. Indeed, many of these scenarios did not address specific policies needed to obtain the world picture they portrayed, while others examined only policy targets rather than providing pathways to achieve those targets. Similarly, the range of uncertainties regarding oil security, gas supply, rate of adoption of renewable technologies, and nuclear power is not well-covered by the scenarios examined in this study.

If the drawback of the planning scenarios is a lack of policy specificity, this problem is addressed to some extent by narrower studies of technologies, as well as partial scenarios examining effects of specific policies. Our analysis of these studies resulted in four policy implications that illustrate how such scenarios and studies can provide policy insights despite the uncertainty associated with these issues:

- First, research and development serves as a hedging strategy. Because technological improvement and market penetration are all subject to

DOE/EERE Policy Instruments

The document Clean Energy for the 21st Century, Office of Energy Efficiency and Renewable Energy, Budget-in-Brief Fiscal Year 2001, DOE/EE-0212 describes the EERE program activities and their FY 1999, FY 2000, and FY 2001 (requested) budgets.

The EERE programs are: Industrial Technologies (OIT); Transportation Technologies (OTT); Building Technologies, State and Community Programs (BTS); Power Technologies (OPT); and the Federal Energy Management Program (FEMP). The policy instruments used by these programs to achieve EERE goals are also described in the aforementioned document.

The policy instruments available to EERE grow from its programs and activities. They fall in seven major areas:

- Funding of cost-shared research, development and demonstration (RD&D) programs
- Technical assistance
- Information resources and outreach
- Standards, codes, guidelines development
- Energy efficiency improvement projects
- Education, training, financing mechanisms to reduce market barriers
- Creation of long-term U.S.-developing and transition country EERE relationships

OIT, OTT, BTS, and OPT all devote a substantial portion of their budgets to cost-shared research, development, and demonstration (RD&D) programs with national laboratory, private industry, and academic participants. They also provide technical assistance, information resources, and outreach efforts to enhance development and deployment of clean and efficient energy technologies. OPT also sponsors field validations of a dvanced power technologies. BTS funds projects to weatherize homes and state grants to increase energy efficiency in all of the end-use sectors . BTS is also active in the development of building codes, appliance standards and guidelines to increase energy efficiency and accelerate the adoption of clean technologies. FEMP assists Federal Agencies in identifying, financing and implementing energy efficiency and renewable projects in Federal facilities and operations.

EERE has several cross-cutting initiatives aimed at reducing market barriers to accelerate deployment of clean and efficient energy technologies, as well international programs that encourage greater use of U.S. energy efficiency and renewable technologies by developed, developing and transition countries to help meet energy needs worldwide, reduce the rate of consumption of fossil energy resources, and address environmental issues.

SOURCE: DOE.[8]

Figure A.32—Policy Instruments Available to DOE/EERE

[8] *Clean Energy for the 21st Century* is available on-line at http://www.doe.gov.

uncertainty, PCAST recommends maintaining a diverse portfolio of research and development efforts. Findings such as these help illuminate how policy can take account of technological uncertainties.

- Second, if decarbonization policies are pursued, many of the scenarios examined here suggest natural gas as a transition fuel, whether the gas is used by fuel cells or advanced combined-cycle turbines. Jesse Ausubel's long range study of historical energy trends and their implications for the future suggests that natural gas could be on the brink of a take-off, mirroring earlier experiences with coal and oil. Decisionmakers will need to ensure that policy choices fully reflect such a change from the current situation.
- Third, Romm, Rosenfeld, and Herrman argue that changes need not be driven by canonical factors. The world is accustomed to thinking of change in the energy field in terms of change being driven by geopolitics, public policy choices, and consumer preferences. But the Internet and information technology may be changing the way we use energy, resulting in some of the most fundamental change we have witnessed in history.
- Fourth, the partial scenario provided by Lovins and Williams, in the context of other technology studies of distributed generation (ADL) and fuel cells (CARB) argue that technologies with a wide potential application may enable changes in the generation system that can change the basic nature of the system. Because fuel cells have such a range of potential applications (remote, reliable, uninterrupted stationary power today, distributed generation tomorrow, then automotive use), they may ultimately enable transition to a hydrogen economy.

None of the planning scenarios explored the effect of "surprises," e.g., oil price "shocks" such as occurred in 1973 and 1979. Whatever the future holds in store, it is likely to include a lot less continuity than that depicted in these scenarios or even the *Hard Times* meta-scenario we developed to explore these possibilities. The historical record of U.S. energy consumption shows periods of rapid growth, crisis and adjustment, and then continued growth, albeit at a slower rate, and accompanied by increased energy efficiency. Even in the relatively recent past, the U.S. followed a reduced demand, reduced liquid fuel scenario from about 1977-1986, then turned about and has followed an increased liquid fuel scenario since. Business-As-Usual scenarios such as the EIA Reference Case and the econometric scenarios, as well as the Royal Dutch Shell and WEC/IIASA scenarios, assume that ample fossil fuels will be available to fuel energy growth. A significant group of scenarios also assume that the U.S. will not significantly change its fuel mix to 2020, implying increased use of coal. Unanticipated events, e.g., Middle East war, (real or perceived) global climate catastrophe, failure to

obtain approvals for new coal-fired power plants, failure to add to gas reserves at anticipated rates, LNG or oil tanker accidents, could lead to future energy supply constrictions. Aggressive policy actions to increase the fraction of clean energy in our fuel mix and to increase energy efficiency are the best hedge possible against such futures.

There were some scenario variants with reduced energy consumption, in some cases associated with a transition to an environmentally conscious fuel mix. Many of these scenarios assume rapid adoption of improved technology, sometimes coupled with changes in patterns of energy consumption. These futures are unlikely to come about without aggressive policy action, for example, the type of broad energy RD&D program envisioned by PCAST, or the carbon emissions price used by EIA in its analysis of the costs of compliance with the Kyoto Protocol.

In particular, transition to a future of high energy efficiency and judicious fuel mix choices, as envisioned by ACEEE at al. and WEC/IIASA, will require positive policy actions, e.g., RD&D support such as proposed by PCAST, carbon reduction strategies and other policies, to promote a sustainable fuel mix. It is not by any means clear that such a future is obtainable through pursuit of existing policies. In fact, such policies, plus new fuel discoveries (e.g., methane hydrates) and a sustained economic boom, could well be driving forces toward increased energy growth.

Because most scenarios, especially EIA's, show increased use of oil and natural gas, the source and security of oil and gas supply, including imports, is a key policy issue. Increased oil imports are assumed to come primarily from the Persian Gulf. Increases in domestic supply of natural gas are assumed to come from additions to proven reserves. Alternative oil or liquid fuel supply options and necessary price and policy incentives for natural gas production are critical issues that require analysis.

Most scenarios wrote off the nuclear option by assuming that nuclear power plants will be decommissioned on schedule and that no nuclear power plants will be built. While this is consistent with current trends in the U.S. and Europe, it is too narrow an assumption to inform policy. As demonstrated in the EIA Kyoto Protocol scenario variants, extending the lifetime of existing plants can be an essential and cost-effective component of a carbon reduction strategy. Especially in light of the current level of international concern about greenhouse gases, nuclear power, as a carbon-free source of electricity, needs to be analyzed and considered within an objective framework that compares the costs, risks, and impacts of alternative energy sources.

Table 1

Models and Scenarios RAND Compiled and Evaluated

Model/Scenario	Source	Notes
EIA	*Annual Energy Outlook 2000* (EIA, 2000)	The Energy Information Administration (EIA) Reference Case has five variants, and 32 side cases (20 of which were fully quantified). These scenarios are extrapolations of current trends and policies, using a combination of econometric and technological models.
EIA Kyoto Protocol 1	*Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity* (EIA, October 1998)	This includes six scenario variants that use the EIA economic and technological models, with an added carbon price component included in the price of each fuel. The report also describes five sensitivity cases that vary economic growth, rate of technological improvement, and nuclear power use.
EIA Kyoto Protocol 2	*Analysis of the Impacts of an Early Start for Compliance with the Kyoto Protocol* (July 1999)	The second of EIA's two analyses of the impacts of Kyoto, revisited the same assumptions together with implementation beginning in 2000. The carbon prices were reduced somewhat but the conclusions were unchanged.
Econometric Scenarios	International Energy Agency (IEA); Gas Research Institute (GRI); American Gas Association (AGA); Independent Petroleum Association of America (IPAA); Standard and Poors' DRI Division; Wharton Econometric Forecasting Association (WEFA); Source: EIA, Annual Energy Outlook 2000 (EIA, 2000)	Scenarios based upon econometric models developed by multi-national and nongovernmental organizations were included in the study.
WEC	*Global Energy Perspectives* (Cambridge University Press, 1998)	The World Energy Council (WEC) and the International Institute for Applied Systems Analysis (IIASA) describe 6 world energy scenario variants that span a broad range of alternative futures.

Table 1—Continued

Model/Scenario	Source	Notes
Royal Dutch Shell	Royal Dutch Shell Energy Group, available online at www.shell.com, accessed July, 2000.	Royal Dutch Shell developed one scenario variant in which growth in energy consumption is sustained at a high rate, and another variant in which "dematerialization" slows energy consumption.
IPCC	The Intergovernmental Panel on Climate Change (IPCC) , *The Preliminary SRES Emissions Scenarios* (January 1999)	IPCC described six scenario variants with different assumptions about economic, population, and technological growth.
America's Energy Future	The American Council for an Energy Efficient Economy (ACEEE), Alliance to Save Energy, National Resource's Defense Council, and the Union of Concerned Scientists, in consultation with the Tellus Institute, *America's Energy Future*, (1997)	ACEEE described three scenario variants based upon high energy efficiency and investment in renewable energy, together with substantial changes in the energy infrastructure.
Bending the Curve	Stockholm Environment Institute and Global Scenario Group, *Conventional Worlds: Technical Description of Bending the Curve Scenarios* (1998)	The Stockholm Environment Institute and Global Scenario Group describe two scenario variants driven by intervention to reduce carbon emissions and transition to renewable energy sources.
Interlab Working Group 1	Inter-Laboratory Working Group, *Scenarios of U.S. Carbon Reduction: Potential Impacts of Energy-Efficient and Low-Carbon Technologies by 2010 and Beyond* (1997)	First of two reports by the five DOE national laboratories describes two scenario variants in which public policy actions and market intervention lead to reduced carbon emissions.
Interlab Working Group 2	Inter-Laboratory Working Group, *Scenarios for a Clean Energy Future* (2000)	Second of two reports by the five DOE national laboratories; describes three scenario variants involving public policy actions and market interventions designed to bring about reduced carbon emissions.
PCAST	President's Council of Advisors on Science and Technology (PCAST), *Powerful Partnerships: The Federal Role in International Cooperation on Energy Innovation* (June 1999)	PCAST makes quantitative estimates of reductions in fossil fuel use, U.S. oil imports, and CO_2 and other emissions possible with increased investment in energy RD&D.

Table 1—Continued

Model/Scenario	Source	Notes
Ausubel	Jesse Ausubel, "Where is Energy Going?" (*The Industrial Physicist*, February 2000)	Ausubel of Rockefeller University describes the decarbonization of the fuel mix in "pulses" of rising energy consumption per capita, with natural gas as the 21st century transition fuel to hydrogen.
Romm et al.	Joseph Romm, Arthur Rosenfeld, and Susan Herrman, *The Internet and Global Warming* (1999)	Romm et al. argue that e-commerce spurred recent improvements in U.S. energy efficiency, and posit future increases in efficiency beyond extrapolation of current trends, with concomitant reductions in energy consumption.
Lovins and Williams	Amory Lovins and Brett Williams, *A Strategy for the Hydrogen Transition* (April 1999)	Lovins and Williams envision stationary fuel cells powering buildings and providing distributed generation of electricity, resulting in the reduction of size and cost of fuel cells and hydrogen infrastructure, and ultimately cost-effective fuel-cell-powered ultra-high efficiency "hypercars."
CARB	California Air Resources Board (CARB), *Status and Prospects of Fuel Cells as Automobile Engines* (July 1998)	CARB examined the cost of hydrogen infrastructure for automotive fuel cells, as well as methanol and gasoline as hydrogen sources.
ADL	Arthur D. Little (ADL), *Distributed Generation: Understanding the Economics* (1999)	ADL provides a detailed market study of fuel cells, co-generation, small gas turbines, and microturbines for distributed electricity generation.
EIA Natural Gas Hydrates	U.S. Energy Information Administration (EIA), chapter 3 "Future Supply Potential of Natural Gas Hydrates" in Energy Information Association, *Natural Gas 1998: Issues and Trends* (April 1998)	EIA describes the vast reserves of methane trapped in hydrated form in deep undersea and Arctic deposits, and discusses the technological prospects for recovery.
KPMG	KPMG, *Solar Energy: From Perennial Promise to Competitive Alternative* (August 1999)	A Dutch firm, KPMG, with the sponsorship of Greenpeace, proposes construction of large-scale (500 MW) photovoltaic power plants as a way of decreasing the cost of solar electricity.

Table 1—Continued

Model/Scenario	Source	Notes
EERE Program Plans	National Renewable Energy Laboratory (NREL), *Photovoltaics: Energy for the New Millenium* (January 2000)	NREL published several reports detailing the current state of federal renewables research. In the report on photovoltaics, NREL projects growth rates of photovoltaic systems and reductions in system costs, including an industry-developed roadmap with photovoltaics providing 10% of electricity by 2030. The Federal Wind Energy Program envisions prices of wind energy to fall to 2-4 cents by 2002. Further research and development could lower this price to 1-3 cents by 2015.

NOTE: These models and scenarios are widely used for energy policy planning purposes. Each model or scenario incorporates different assumptions about variables like fuel mix, political climate and economic change. The following table summarizes the sources and general characterization of the models and scenarios examined.

Table 2

Summary of Five Meta-Scenarios

Parameters	Hard Times	Business-as-Usual	Technological Improvement	High-Tech Future	New Society
Defined as:	Low growth/moderate environmental impact	Moderate growth/high environmental impact	Moderate growth/low environmental impact	Moderate growth/moderate environmental impact	Low growth/low environmental impact
Potential for Disruption (SP1)	High	Medium, because of the high level of oil imports and high reliance on natural gas, both of which pose potential problems of price increases and supply security or availability.	Medium, because of the need to substantially increase either energy productivity or decarbonization or combination of the two.	Medium, because of the high level of oil imports and high reliance on natural gas, both of which pose potential problems of price increases and supply security or availability.	High, because of the high level of policy intervention required to reach this future.
Energy Contribution to the Consumer Price Index (SP2)	Probably increased because of scarce energy and low economic growth.	Not addressed.	Objective would be to keep it the same as today	Objective would be to keep it the same as today	Low

Table 2—Continued

Parameters	Hard Times	Business-as-Usual	Technological Improvement	High-Tech Future	New Society
Cost of Health and Environmental Impacts and Regulatory Compliance (SP3)	Reduced because of lower energy consumption and lower economic growth, unless the pathway to this scenario was an environmental catastrophe, in which case these costs would be very large.	EPA has recently estimated the cost of regulation at $150-200 billion/year.	Should be reduced because of lower energy consumption and use of cleaner technology, as evidenced by increased decarbonization and energy productivity.	Higher energy consumption balanced by use of cleaner technology, as evidenced by increased decarbonization and energy productivity, could leave this the same as today.	Should be greatly reduced because of lower energy consumption and use of cleaner technology, as evidenced by increase decarbonization and energy productivity.
GDP Growth (EC1)	Close to zero	1.7-2.6%/year, with the EIA base case at 2.2.%/year.	2.2%/year (EIA Base Case)	3.2%/year (.5 higher than EIA high GDP variant).	1.7%/year
Inflation Rate (EC2)	A few percent or less	2.7%/year.	2.7%/year (EIA Base Case)	Not Addressed	Not Addressed
Energy Price Inflation /Overall Price Inflation (EC3)	Could be increased because of energy shortages.	Oil prices assumed to be in the range of $15-28/barrel in 2020.	Could increase due to higher fuel taxes.	Not Addressed	Not Addressed
Fuel Taxes, Energy Subsidies, and R&D Expenditures (EC4)	No major changes in taxes, but subsidies and R&D expenditures are reduced	Order of magnitude estimate is tens of billions of dollars per year, based upon available data and studies.	May require increased fuel taxes; will definitely require increased R&D expenditures.	May require increased energy subsidies; will probably require increased R&D expenditures.	Will require increased fuel taxes, removal of energy subsidies, and increased R&D expenditures.

Table 2—Continued

Parameters	Hard Times	Business-as-Usual	Technological Improvement	High-Tech Future	New Society
Total Energy Consumption (EN1)	100 quads	112-129 quads	97-110 quads	120-127 quads	65-83 quads
Decarbonization (EN2)	1.6	1.5-1.6 (1.61 in 1997)	1.5-2.0	1.6-1.9	1.8-2.6
Energy Productivity of the Economy (EN3)	$90/MBTU	$104-118/MBTU	$105-133/MBTU	$112-144/MBTU	$150-192/MBTU

B. Delphi Analysis

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The following pages present the slides from the Delphi presentation at the conference. A discussion appears in Volume 1. A transcript of the presentation itself and the conference discussion can be accessed at http://www.rand.org/scitech/stpi/Evision/Transcripts/Day1-am.pdf.

Futures Methodologies
(TFI taxonomy)

- Extrapolation
- Pattern Analysis
- Goal Analysis
- Counter Punching
- Intuition
  - Delphi Survey
  - Nominal Group Conferencing
  - Structured and Unstructured Interviews
  - Technology Advantage Management

Modified Delphi Technique

- Original Delphi Technique (1963)
  - Anonymous response
  - Iteration and controlled feedback
  - Statistical group response
- Modified Delphi Technique
  - More qualitative
  - Anonymous response
  - Iteration and controlled feedback

Setup for Modified Delphi

- "You have it on unimpeachable authority that a time traveler will appear to you early in the new millennium. That traveler comes from 20 years in the future and knows everything you could possibly want to know about the situation surrounding energy needs in the year 2020. You will get to ask that time traveler 10 questions about that future. The single drawback to this extraordinary situation is that the time traveler is mute. S/he can only nod yes or no to your questions."
- Round 3 – reduced to six questions

Participants

- Private Sector/Industry Trade Assns (8)
  - American Electric Power, Ford, Weyerhaeuser, Robert Charles Lesehr & Co., McDonough and Partners, SAIC, Gas Research Institute
- Government (6)
  - National Energy Technology Laboratory, National Renewable Energy Laboratory, Former Presidential Science Advisor, Oak Ridge National Laboratory
- Academia/Other Non-Profit (13)
  - Colorado School of Mines, International Research Center for Energy and Economic Development, University of Houston, American Council for an Energy-Efficient Economy, Chairman of the Energy Foundation, Arizona Corporation Commission, Center for Energy and Climate Solutions, Sigma Xi, Purdue University, Carnegie Mellon University, Resources for the Future, CONSAD Research Corp., James Madison University

Results

- Consensus?
- By question
  - *And participant's institutional affiliation*
- By question-area
- Support for EERE categories

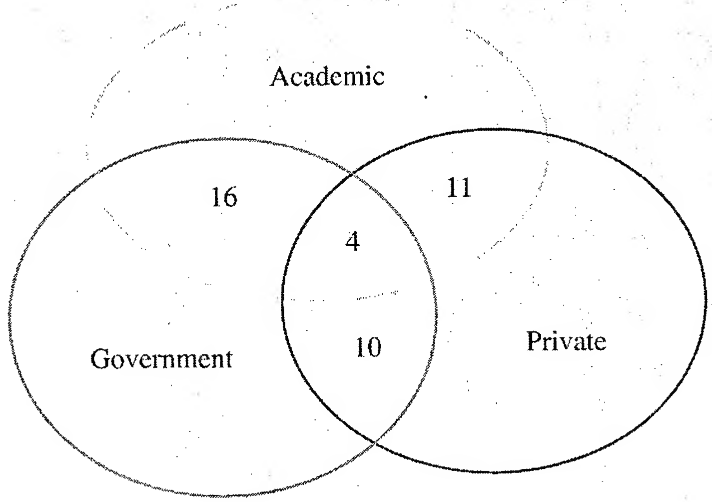
Was Consensus Reached?

- There was some convergence
  - *R#1 - 262, R#2 - 185, R#3 - 99 (< 111)*
- Little consensus on by-question basis
- Much greater consensus on question-area basis

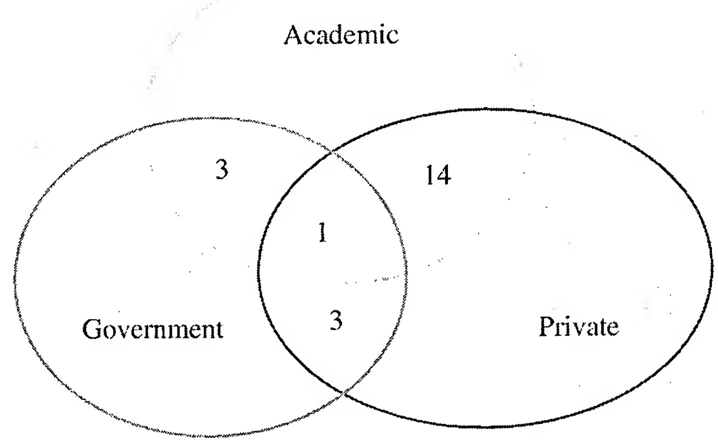
Round 3: By Question Results

- Only one question got as many as 4 votes
  - "Within the U.S. transportation sector, is the market share of hybrid and zero-emission vehicles 20 percent or greater?"
- Nine got three votes
- Eighty got only one vote

Round 2: Number of Overlap Questions



Round 3: Number of Overlap Questions



Round 3 by Question Area

- Global warming and GG emissions (27)
- Hybrid/zero-emission vehicle penetration (13)
- Natural gas usability/use (11)
- Fuel cell viability (7)
- Increased nuclear use (7)
- Oil prices (7)

Maximum Overlap Questions

- Round 2
  - Has the price of natural gas risen by more than a factor of 3 between 2000 and 2020?
  - Is the cost of petroleum greater than $45 per barrel in 2020?
  - Has the theory of long-term global warming and climate change by anthropological activity been validated and generally accepted?
  - Is Industrial Carbon Management practiced on a commercial scale expressly for the purpose of limiting CO_2 emissions?
- Round 3
  - On average, over the period 2000 to 2010, has the price of petroleum remained largely constant when adjusted for inflation?

Support for "Other" EERE Categories

- Energy Security – 6 (R#3 questions asked)
- Smart Growth – 1
- Transportation – 15
- Hydrogen Economy – 8
- Demographic/Population Growth – 5
- Environmental Laws – 12
- Distributed Power – 2

Inferences

- By far, the greatest concern is global warming and CO_2 emission control
- Among technologies, natural gas, fuel cells and nuclear power draw greatest interest
- Clear support for EERE's concerns with the future roles of transportation/energy and environmental law

Strategic Planning Notes

- Delphi participants are generally more concerned about the context of the future than the technologies
- Context concerns speak both to threshold events worth more thought and monitoring, and important scenarios worth working through